THEMA: VULKANISCHE ARCHIPELS

nu:

Macaronesië

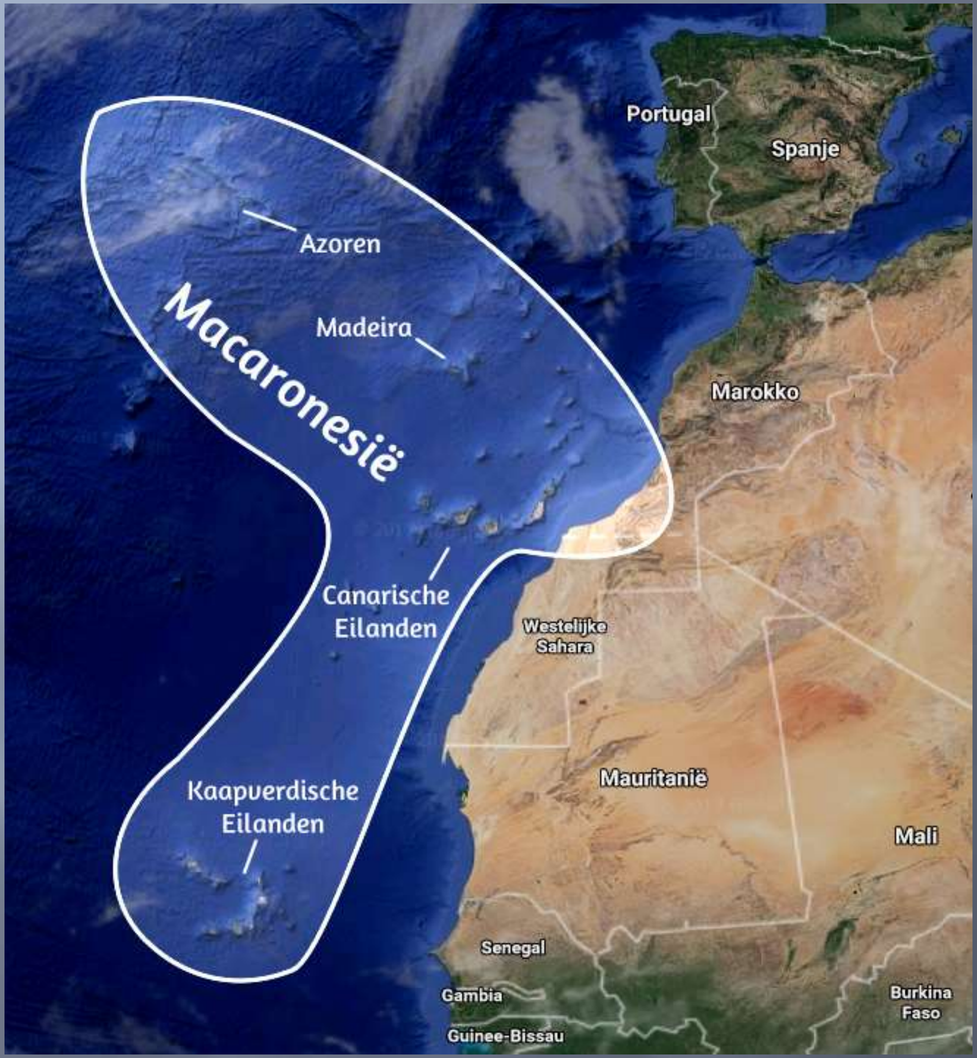
Waar zijn ze?

door: Rob Hekkenberg GEA

Geraadpleegde Literatuur

Aan het eind van de presentatie staat een lijst van de literatuur en de figuren die gebruikt zijn voor deze presentatie. Tussen haakjes staat de referentie.

THEMA: VULKANISCHE ARCHIPELS



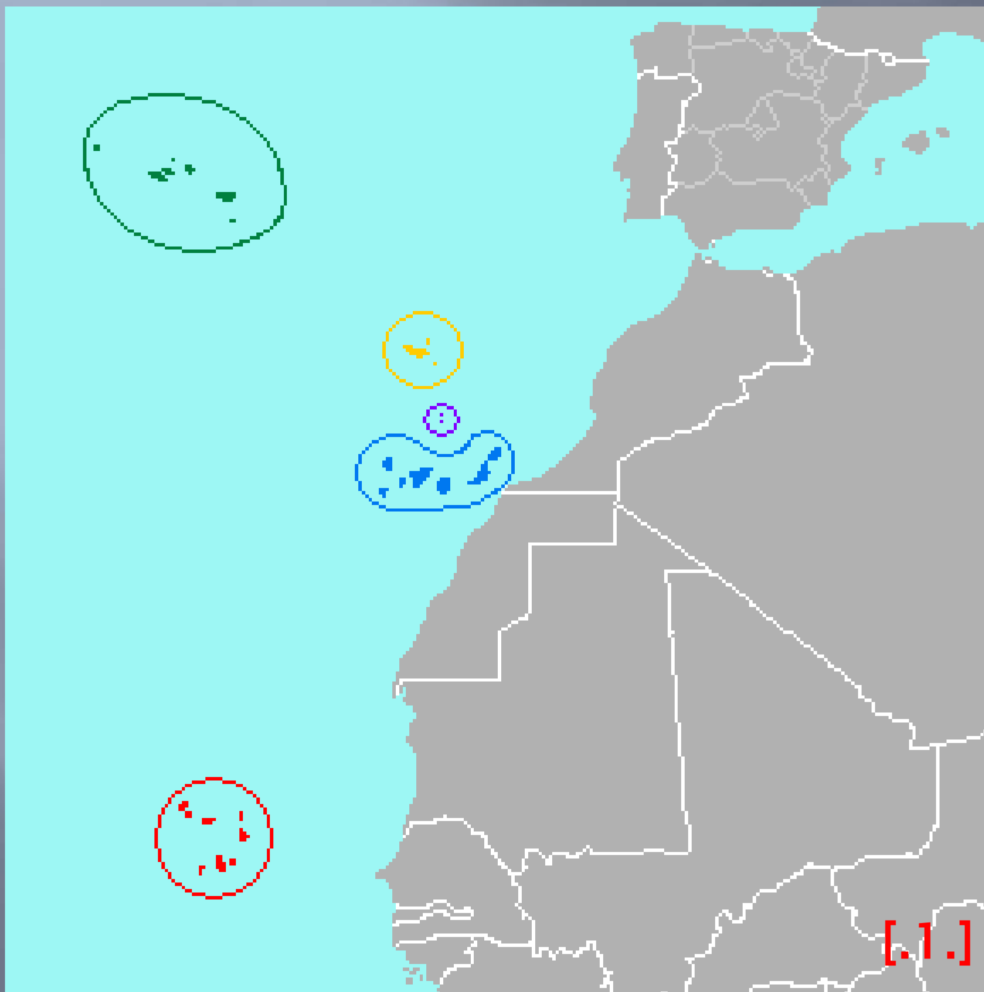
nu:

Macar onesië

Waar zijn ze?

door: Rob Hekkenberg

Macaronesië



groen=Azoren; geel=Madeira; paars=Ilhas Selvagens; blauw=Canarische Eilanden; rood=Kaapverdië

Grieks: *gelukzalige eilanden*

In de plantkunde een aanduiding voor de eilanden van vulkanische oorsprong in de oostelijke Atlantische Oceaan ten westen van West-Afrika. Ondanks de grote onderlinge afstanden tussen de eilanden hebben ze opvallend veel gemeen v.w.b. de planten- en dierenwereld.

Kaapverdië *(onafhankelijk, 1975)*
Canarische Eilanden *(Spanje)*
Ilhas Selvagens *((Wilde Eilanden) (Portugal)*
Madeira, Porto Santo en de Ilhas Desertas *(Portugal)*
Azoren *(Portugal)*

Macaronesië

CHARLES DARWIN IN THE CAPE VERDE AND GALÁPAGOS ARCHIPELAGOS: THE ROLE OF SERENDIPITY IN DEVELOPMENT OF THEORIES ON THE UPS AND DOWNS OF OCEANIC ISLANDS

[.1.]

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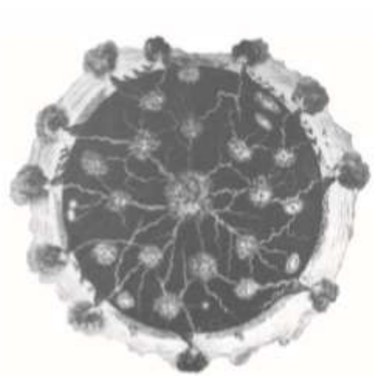

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ABSTRACT

The 1831–1836 voyage of H.M.S. *Beagle* under Captain Robert FitzRoy launched Charles Darwin's entry into the world of geology with two pioneering publications on oceanic islands to his credit. Best known is Darwin's 1842 contribution on the theory of atoll development from the subsidence of volcanic islands and coeval upward growth of coral reefs. This work can be linked, in part, to the ten days during which the *Beagle* visited the Keeling (Cocos) Islands. The subsequent and lesser known of Darwin's parallel contributions is his 1844 summary on all the volcanic islands visited during the expedition, including Santiago (Cape Verde Islands), Terceira (Azores), St. Paul's Rocks, Fernando Noronha, Ascension, St. Helena, the Galápagos Islands, Tahiti, and Mauritius. Ostensibly, the centerpiece of the 1844 volume is Darwin's extensive coverage of Ascension based on the five days spent there in 1836. However, Darwin had many more days at his disposal in the Galápagos and 'St. Jago' (Santiago), where the *Beagle* stopped in the Cape Verde

[.34.] Ontstaan: a.g.v. een hotspot??????

Madeira

Hotspot

- Intense volcanism
- High heat flow
- High topography
- Sometimes trail

Hotspot is something you can see on the earth's surface.

Mantle plume

- Plume of solid, but hotter material rising by buoyancy from depth in the mantle
- Melt formed near the surface, feeds volcanoes of hotspot

Mantle plume is something you can only see deep in the mantle.

(Páll Einarsson, presentation 2012 in Current crustal)

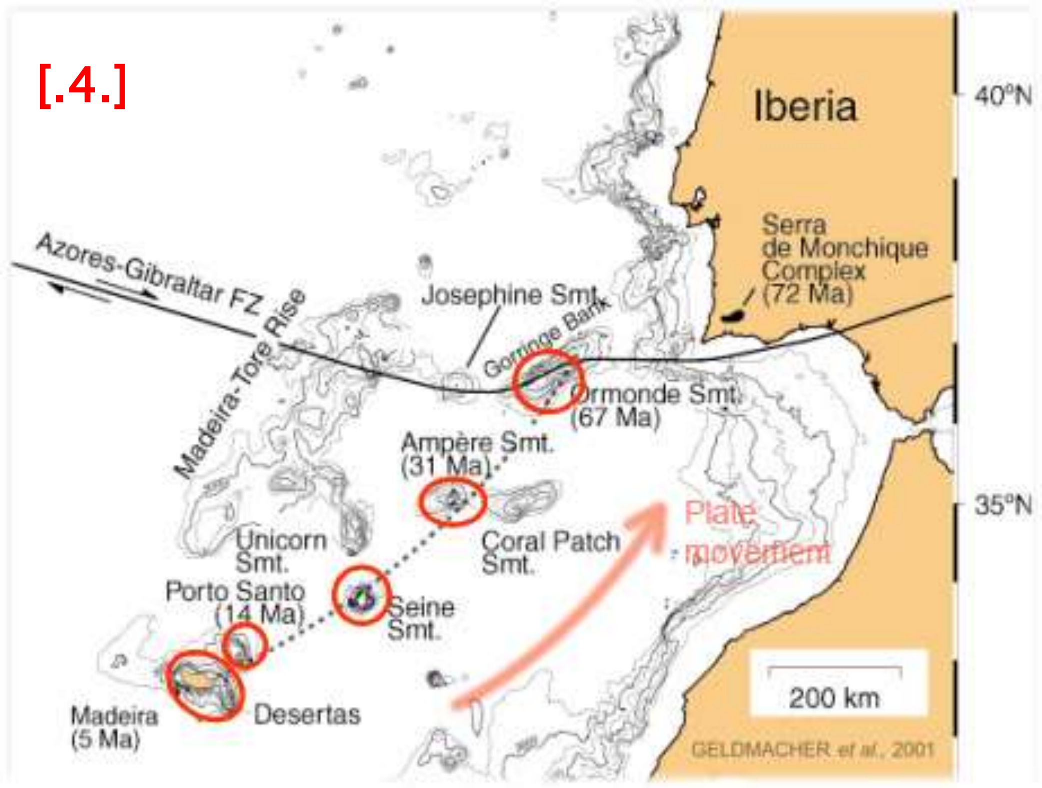
Einar Ragnar Sigurðsson - 4.11.2013 The Azores – A Triple Junction on a Hot Spot Slide no: 8

Er werd verondersteld dat op de plaats van de hotspot een mantelpluim het aardoppervlak bereikt. Die voert dan magma vanuit de diepe mantel aan, bijna aan de grens tussen de mantel en de kern. De samenstelling van het magma is door partieel smelten anders dan de magma's die men aantreft bij vulkanen langs de tektonische platen.
Tegenwoordig is niet iedereen overtuigd van deze theorie. Mogelijk worden hotspots veroorzaakt door een extensie van de lithosfeer waardoor er een verdunning en dus een zwakke plek ontstaat. [.43.]

Madeira

Ontstaan: a.g.v. een hotspot??????

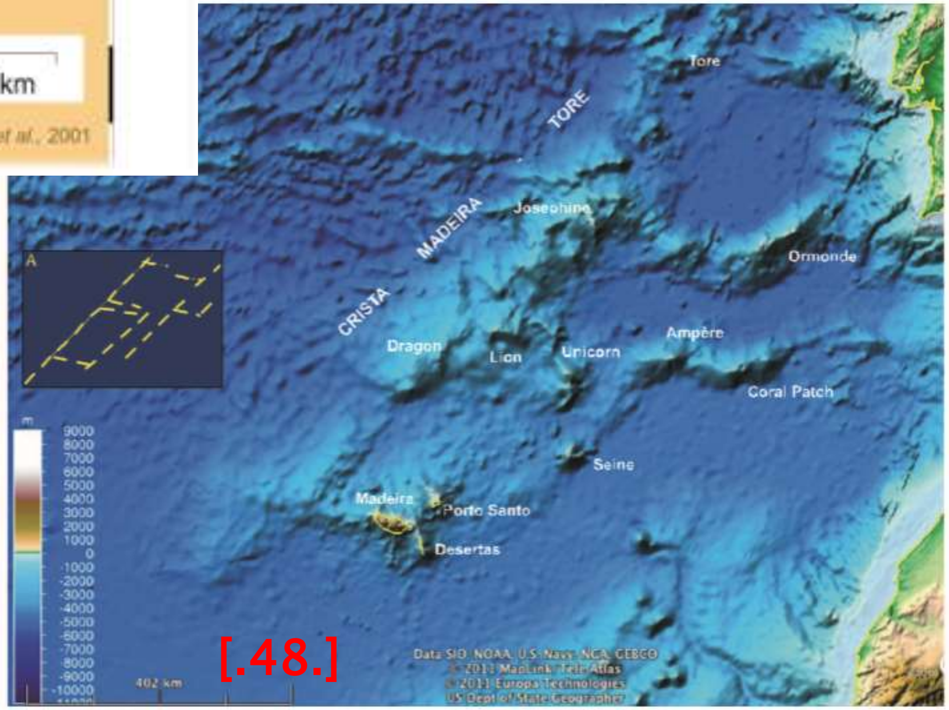
← Mogelijk hotspot "pad"



Is this picture what we get when we check current imagery of the bottom of the ocean?.

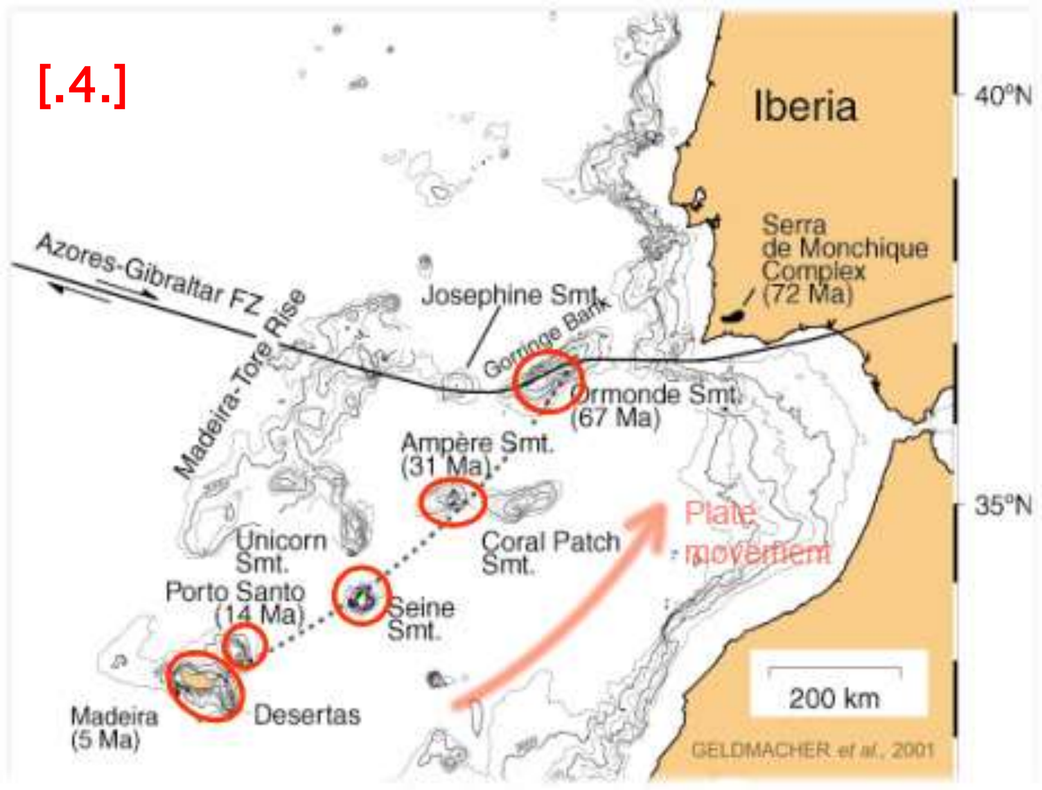
Check this Google Earth image →
(Onderwater "bergen" verbonden)

Madeira ontstaan boven een van de breuken?? →



g. 1 - Mapa do fundo oceânico de um sector do Atlântico Norte, na região envolvente à ilha da Madeira. Excerto de agem Google Earth, modelo de superfície batimétrica ETOPO1 (AMANTE & EAKINS, 2009).

Madeira



Ontstaan: a.g.v. een hotspot??????

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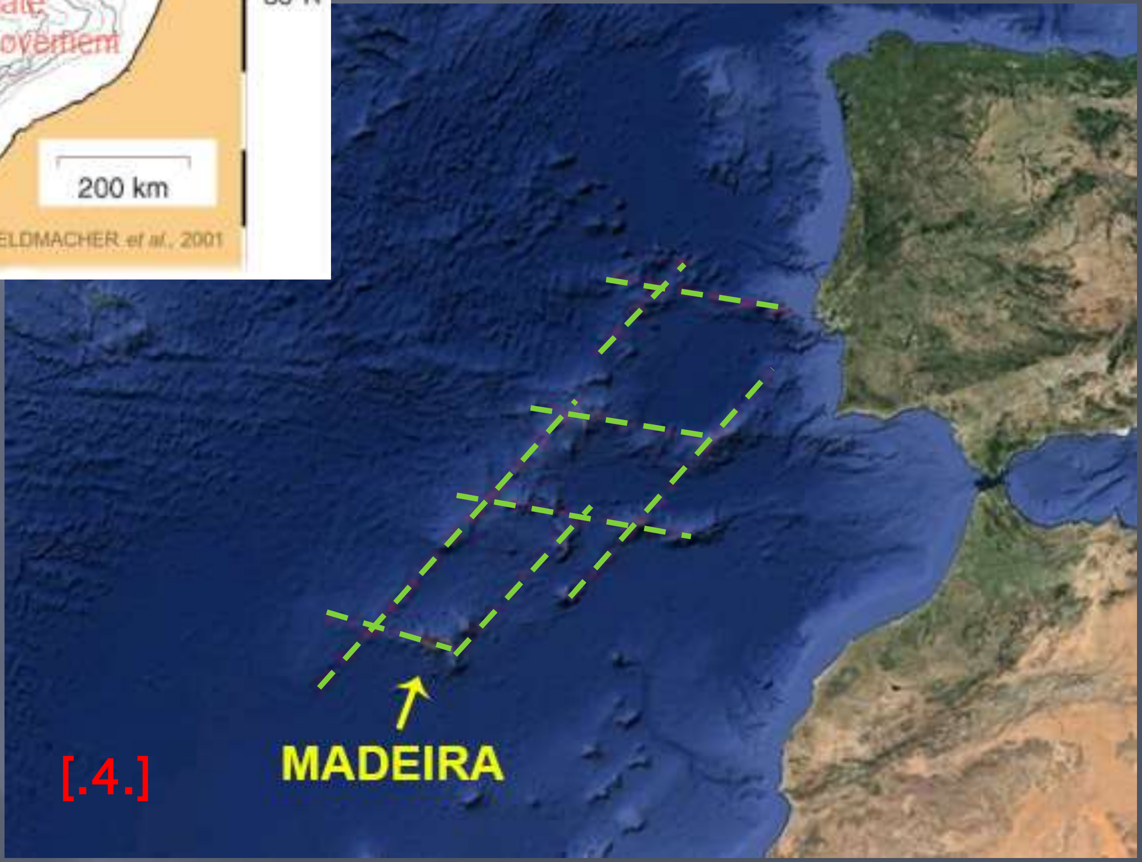
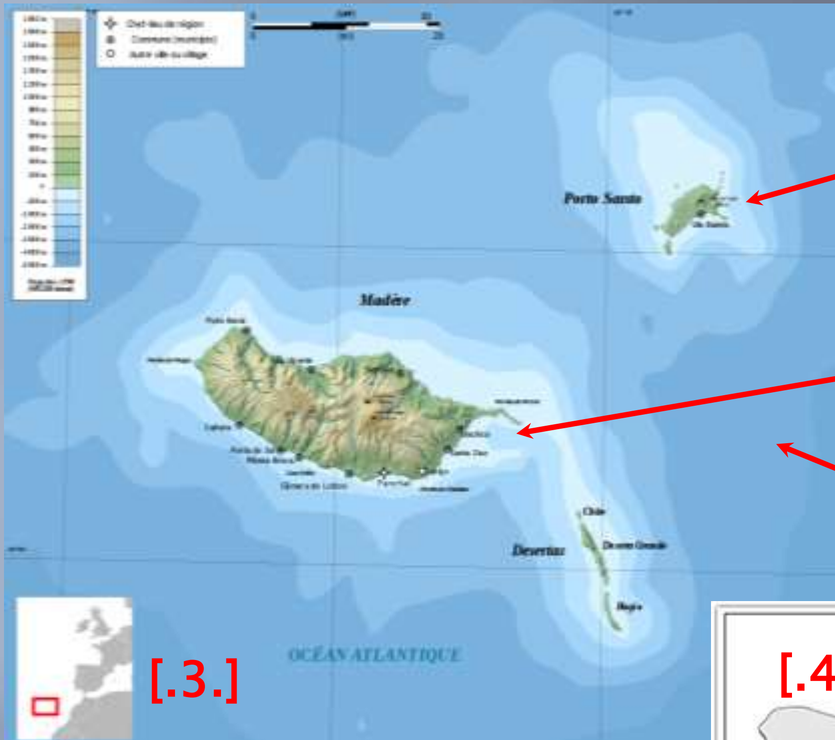


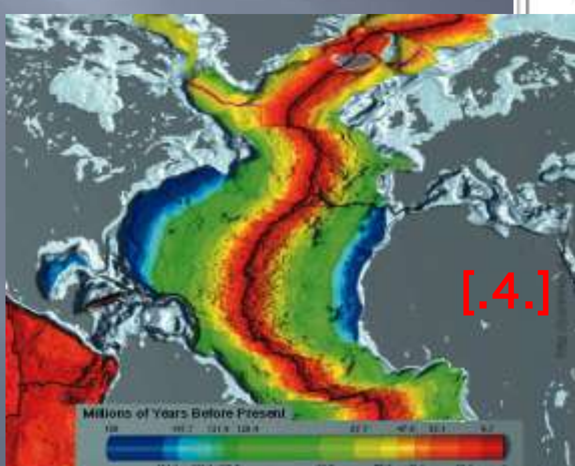
Madeira

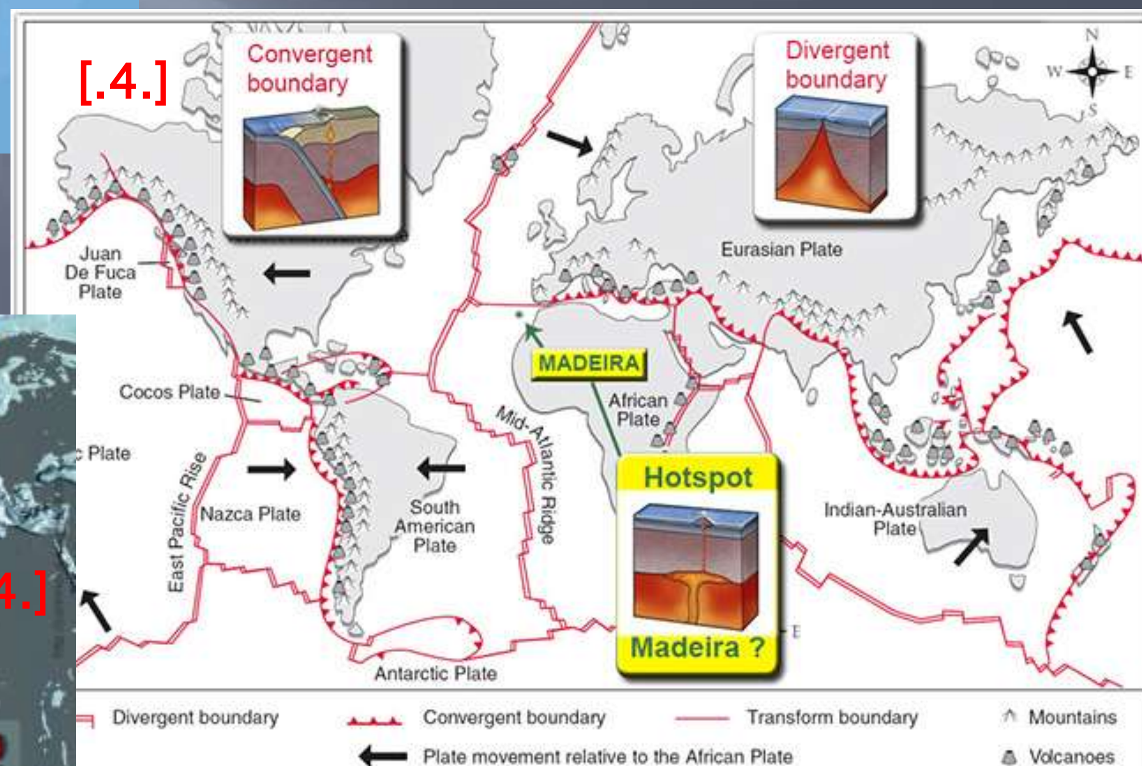
Ontstaan: a.g.v. een hotspot??????

Madeira is een schildvulkaan,
begon op 4000 m diepte.
Op 400 m hoogte: koraal

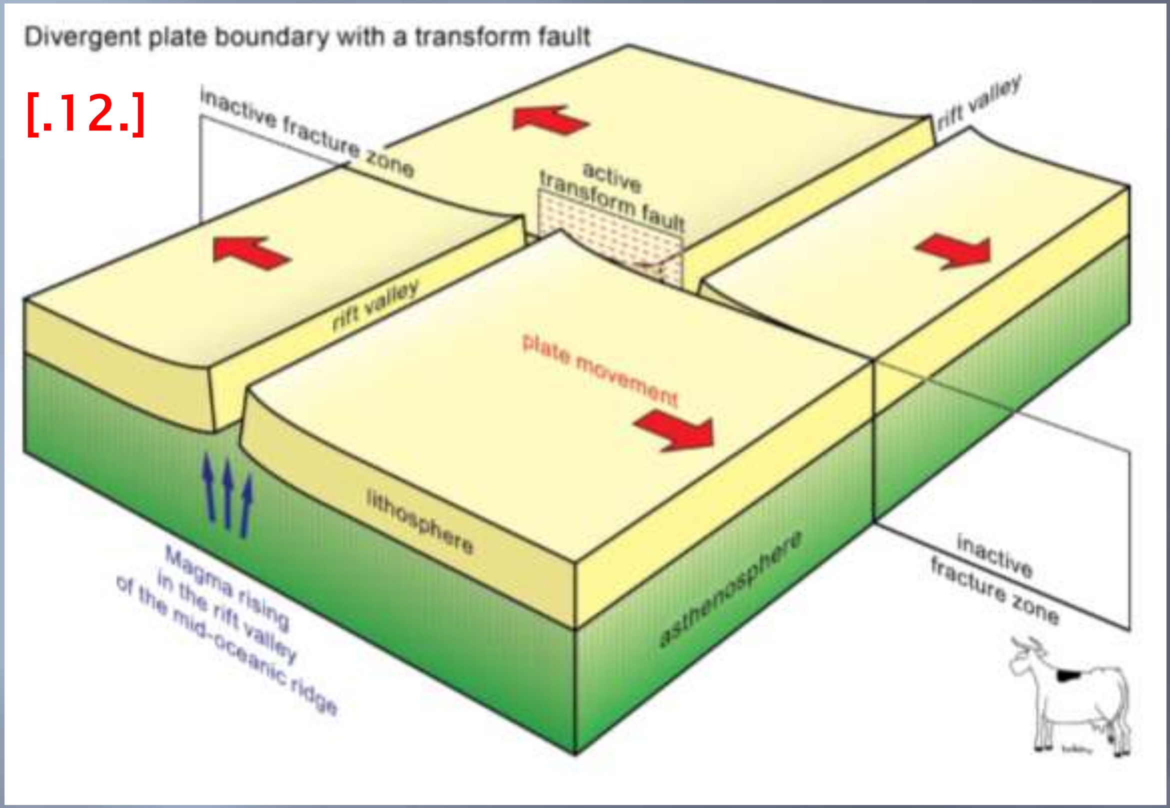


Madeira ligt in het gebied waar de Atlantische Oceaan zich begon te openen





Transform breuk



No divergent plate boundary has a smooth, continuous trace; all are offset by transform faults. RidgeRidge transform faults (fracture zones) are prominent features that repeatedly offset the ocean ridges to accommodate differences in the spreading rates of either side of a ridge and/or between neighbouring segments.

[.12.]

Transform breuk

Ridge-Ridge transform faults have the following characteristics:

(i) They are nearly parallel to the direction of relative motion of the plates on either side. They connect two offset segments of the ridge, which are nearly perpendicular to the spreading direction. The divergent motion away from the ridge is "transformed" to a transcurrent motion along such a fault.

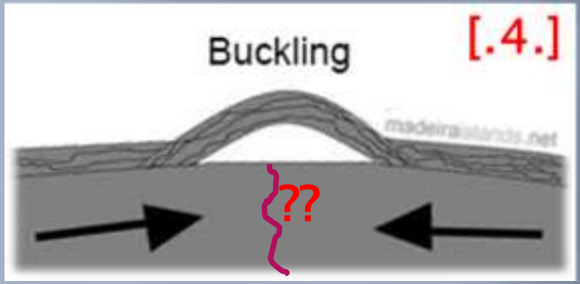
(ii) They terminate the ridges abruptly. They also are plate boundaries and serve as zones of strike-slip accommodation between opposite-travelling domains of seafloor. But: Equal displacement along their length.

(iii) Transform faults can accommodate unlimited amounts of displacement, which may even exceed the length of the fault.

(iv) Adjacent and parallel transform faults may show opposite senses of relative displacement. Sense of displacement can be opposite to what it seems to be from the apparent offset of the oceanic ridge.

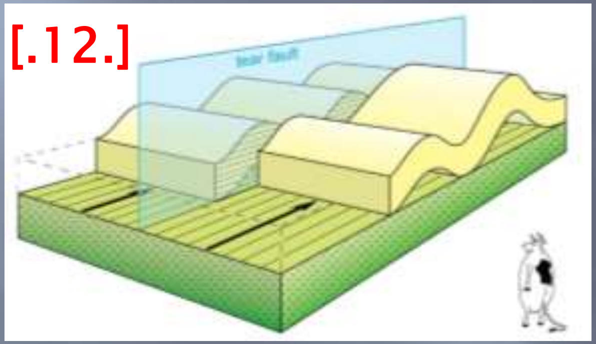
(v) The transform faults and the ridge are coeval. Earthquake activity is much higher along the transform faults than along the ridges. But, because of the relative motion between the plates, the faults are active only between the offset segments of the ridge. Beyond this area, the plates on either side of the fracture are moving in the same direction and at the same rate and may be considered to be linked together.

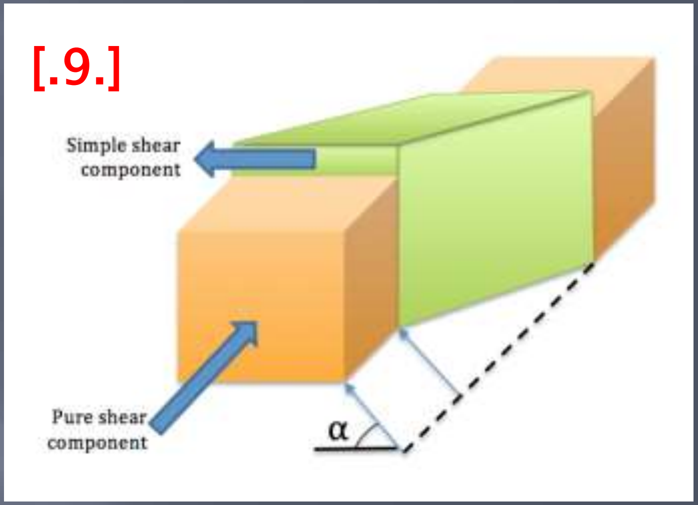
Transform breuk

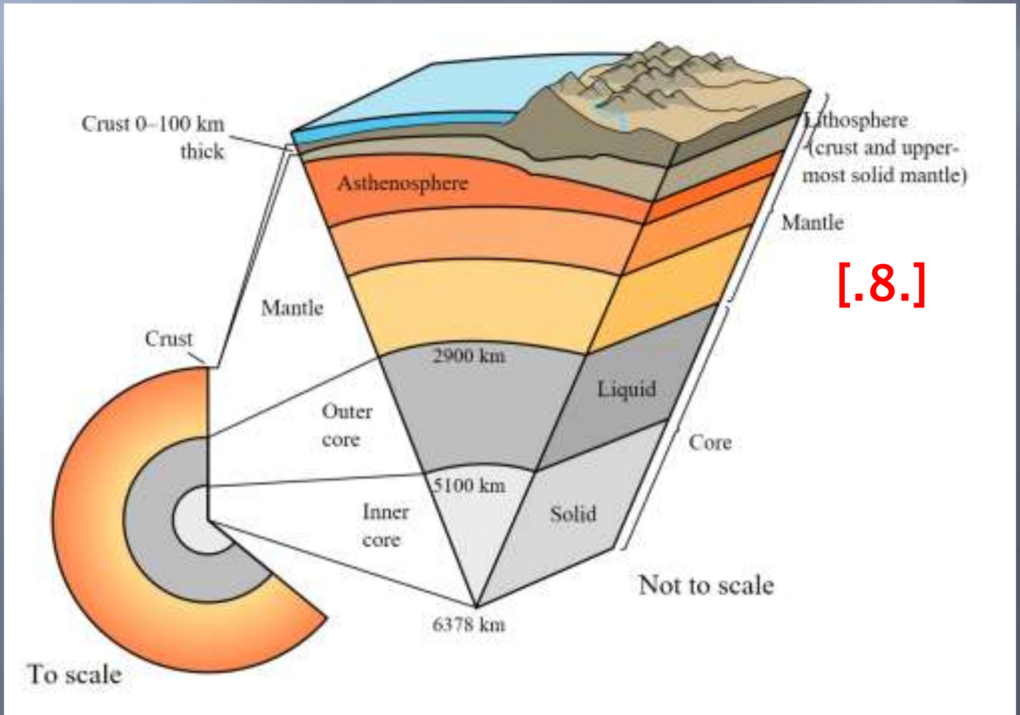


← crust
← upper mantle

Ontstaan: a.g.v. een hotspot??????



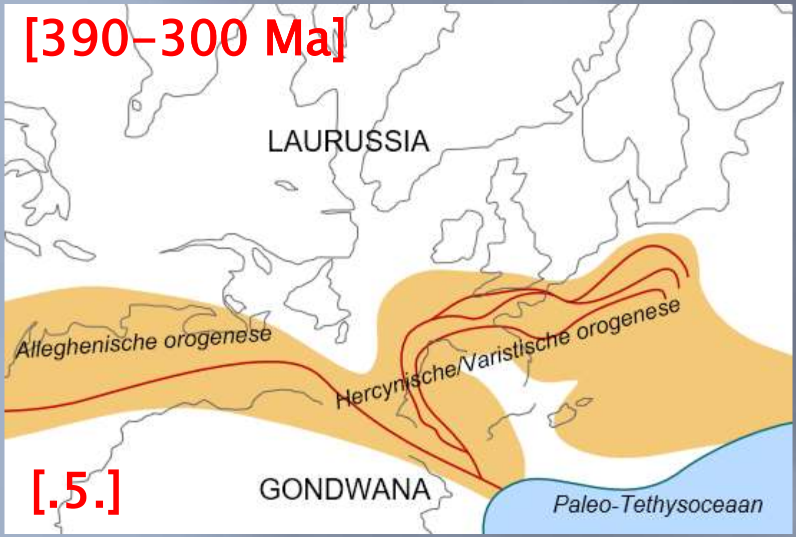




Simple model for *transpression*: strike-slip zone with an additional and simultaneous shortening across the zone. Also induces vertical uplift.

Madeira

Ontstaan: a.g.v. een hotspot??????



Paleozoïcum (540-250 Ma)
Hercinische orogenese

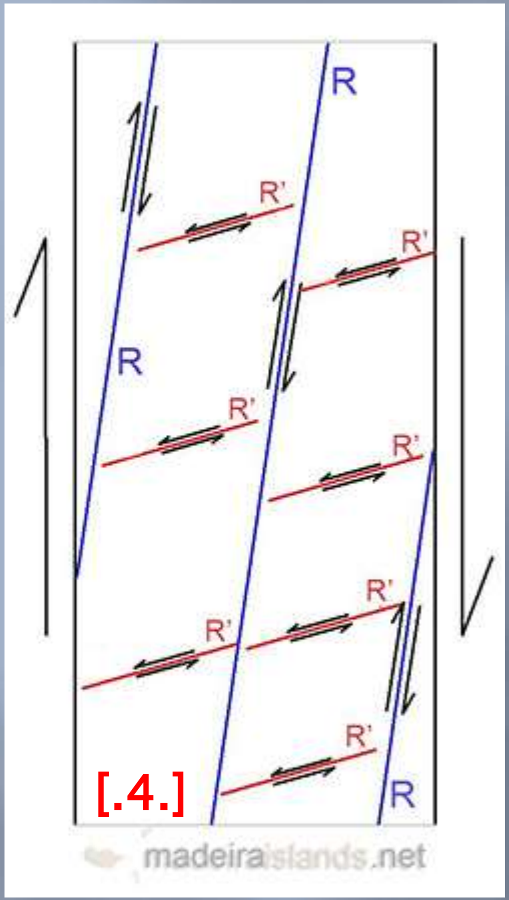
Gereactiveerd in het Mesozoïcum (~200Ma) en weer in het Paleoceen (~70 Ma, alpine)

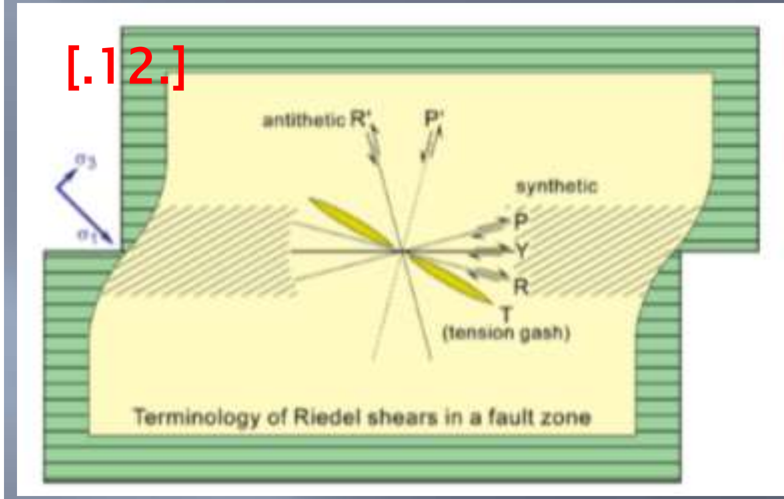
Madeira

Ontstaan: a.g.v. een hotspot??????

This NE-SW orientation is the orientation of the coast of Africa, it is the orientation of the great rifting fault along which in this region the land broke off, along which the Atlantic Ocean began to open.
It means that maybe the major faults that we can found today on the bottom of the ocean, around the islands of Madeira, have also originated when the Atlantic Ocean began to open, about 200 Ma ago.
If this is true the intraplate islands and seamounts around Madeira have probably a tectonic origin, an origin related to magma leaking along active faults in the Mesozoic and Cenozoic. And so a mantle plume origin does not seem to fit so well anymore…

But…….. Madeira island is not aligned along a NE-SW fault. It is aligned along a W-E fault.





Riedel faults

[.12.]
Gaat over breuken,
Publ 2017

-R Riedel shears are normally the first subsidiary fractures to occur and generally build the most prominent set. They develop at an acute angle, typically 10-20° clockwise to a dextral main fault, anti-clockwise to a sinistral strike-slip fault. on the main fault.

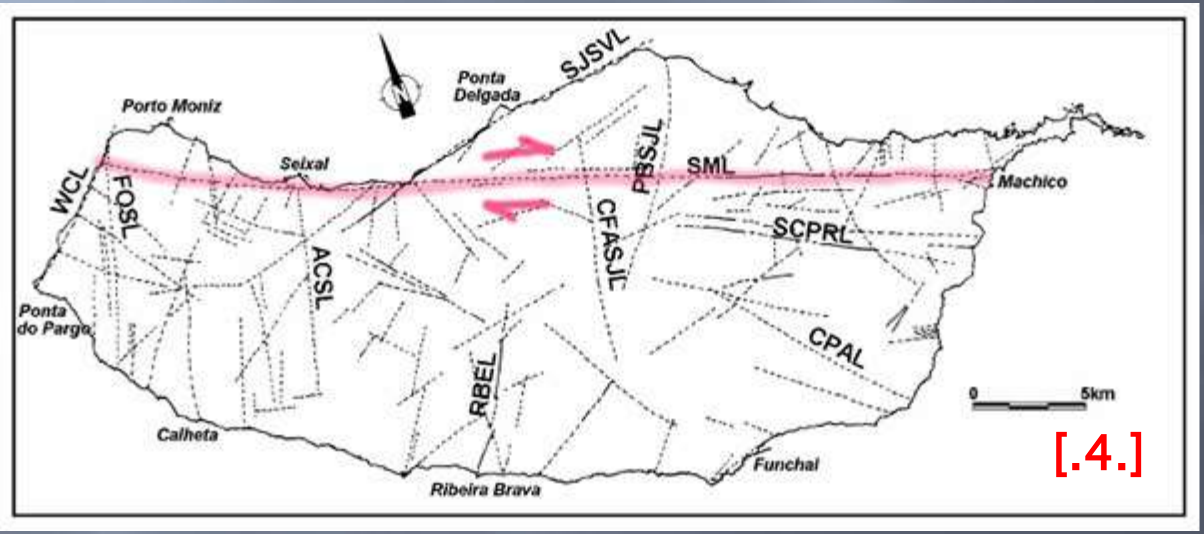
- **R'** shears are antithetic faults (i.e. with a sense of displacement opposite to the bulk movement) oriented at a high angle (approximately 75, conjugate with the R(iedel) shears. They preferentially occur in the overlap zone between two parallel R shears and often connect these two R shears. They may develop with or after R shears.

These W-E faults form an angle of about 60º with the major NE-SW faults. This is compatible with Riedel conjugates. Faults oriented W-E can be **R' faults** and the faults oriented NE-SW can be **R faults** formed along the great Rift of the opening of the North Atlantic Ocean:

Madeira

Ontstaan: a.g.v. een hotspot??????

[.4.]: Later: by Mesozoic and Cenozoic, the kinematics on these structures suffered an inversion. The initial dextral movement of the major faults (NE-SW) became sinistral, and the sinistral movement of the conjugated faults (W-E) became dextral. Oceanic faults would also be affected, changing its movement direction.



Note that the configuration of the island and the orientation of this main fault fits in the major W-E fault that we can perceive in the imagery of the bottom of the ocean.

Maar…….

Madeira

Ontstaan: a.g.v. een hotspot??????

Een andere mogelijkheid is dat de breuken in de oceanische korst niet zo oud zijn.

Ze kunnen ontstaan zijn in relatie met de Alpine orogenese. In die periode zijn een aantal hercinische breuken gereactiveerd en nieuwe breuken werden gevormd. Dat kan ook de oceanische korst hebben beinvloed.

Breuken op de continenten (Iberia en Africa) kunnen verder gegaan zijn naar de oceanische korst. B.v. die langs de Atlas (Betic orogene) of west Iberia, zoals de Nazaré breuk of de Messejana breuk.

Maar Madeira ligt ver van de kust….maar de Canarische eilanden zijn dichtbij Afrika en daar is een grote breuk: de Atlas breuk.

Goed……. Laten we eens iets zuidelijker kijken:
De Canarische Eilanden

Canarische eilanden

Canarische eilanden

Ontstaan: a.g.v. een hotspot??????

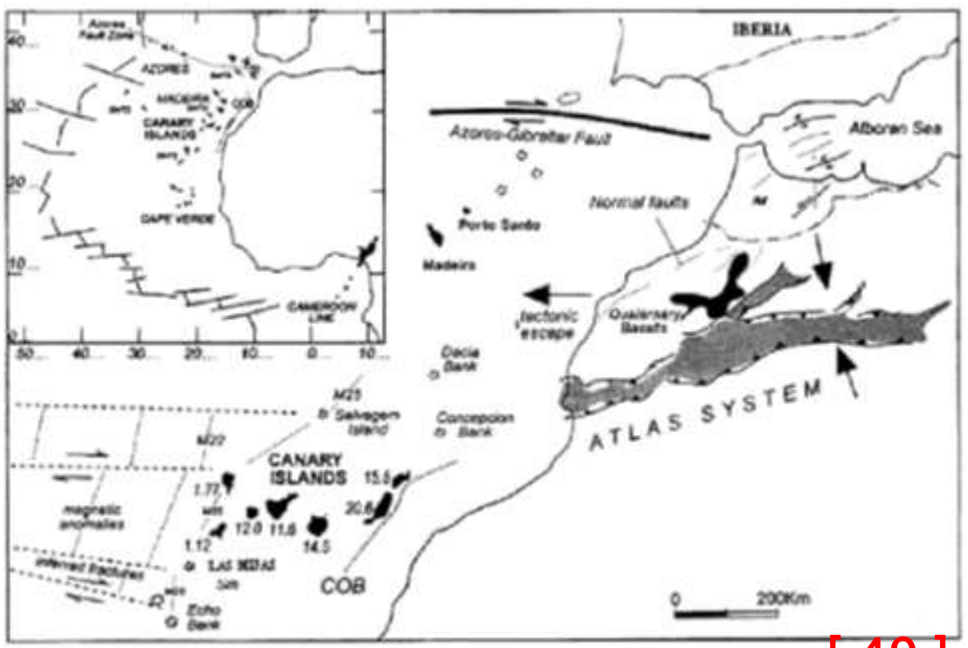


Figure 2: Geographic and geodynamic setting of the NW African continental margin with the Canary Islands and other archipelagos (from Carracedo et al., 2002).

[.49.]

[.49. (2007)]

It is popularly believed that the origin of oceanic intraplate volcanism is related to mantle plumes. On the other hand, the long period of eruptive activity in this archipelago (> 20 Myr in some islands), their morphological and structural features, seismic signature and geochemical evolution **present problems for that model** (Schmincke, 1973; Hoernle et al., 1995; Hoernle & Schmincke, 1993; Carracedo et al., 1998; Canas et al., 1998, and others)

Canarische eilanden

[.49. (2007)]

The origin of the Canaries has been also attributed to:

1. A propagating fracture: The extension to the Canary Islands of an offshore branch of the trans-Agadir fault, associated with the Atlas tectonic chain (Anguita & Hernan, 1975). However there is no evidence of continuous faults connecting the two areas and no of explanation of the uplift of insular blocks.

2. A local extensional ridge: there was a regional extensional structure active in the area in Cenozoic times (Fuster, 1975). But the ocean lithosphere around the Canaries is Jurassic, the rift geometry in each island is different and the islands are separated by deep sea with a lack of Cenozoic lithospher.

3. Uplifted tectonic blocks: Compressive tectonics give way to ocean-floor shortening and crustal thickening, and this process may be the main cause of magmatism and the uplift of blocks forming the Canary Islands. The occasional relaxation of tectonic stress would permit magma eruptions (Araña & Ortiz, 1986). However there is no convincing process for magma genesis.

Canarische eilanden

[.49. (2007)]

The origin of the Canaries has been also attributed to:

4. A hot spot: a mantle plume – the slow-moving hot spot model. Objections to this are that seismic tomography shows a cold lithosphere beneath the Canaries, subaerial volcanic activity shows an irregular westward progression and the thermal anomaly exhibits low melt production. There are long magmatic records (at least 39 Myr on Fuerteventura) which show time gaps in volcanic activity in some islands of up to several million years. There is no bathymetric swell in the Canaries area and no subsidence of the western islands.

5. A unifying model: This suggests the origin of the magmas is a mantle anomaly. Tensional stages generate fractures that serve as conduits for magma liberation and compressive stages produce uplift of islands manifest as sets of flower structures. This model explains the magmatic and tectonic relationships from the Upper Cretaceous to the Miocene in both areas (Anguita & Hernan, 2000). Although it is necessary to explain more about the space-time magmatic and tectonic relationships in each island, in the archipelago zone, and in the Atlas chain from the Miocene to present.

Canarische eilanden

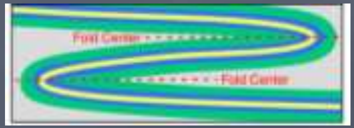
[.49. (2007)]

The Canaries show some interesting differences with the Hawaii Islands:

1. The **geochemical evolution** of their magmas (alkaline suite),

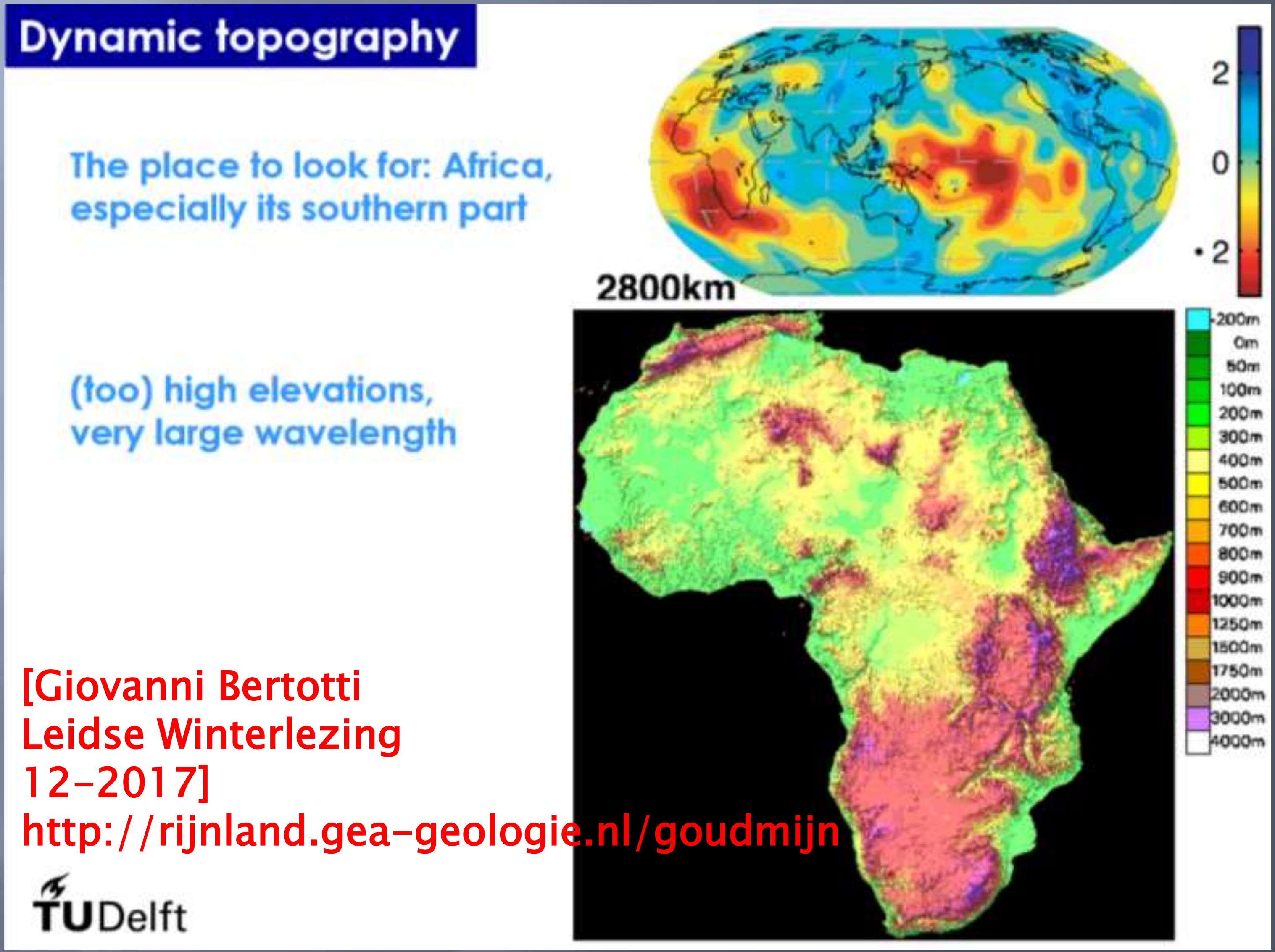
2. The formation of **central stratovolcanoes** (Roque Nublo in Gran Canaria and Teide in Tenerife)

3. **The island tectonics, e.g., ductile shears associated with transtensive** systems (Fernandez et al., 1997), compressional structures such as recumbent folds (Robertson & Stillman, 1979), blocks differentially uplifted from the sea and tectonic lineaments with different azimuths in each island



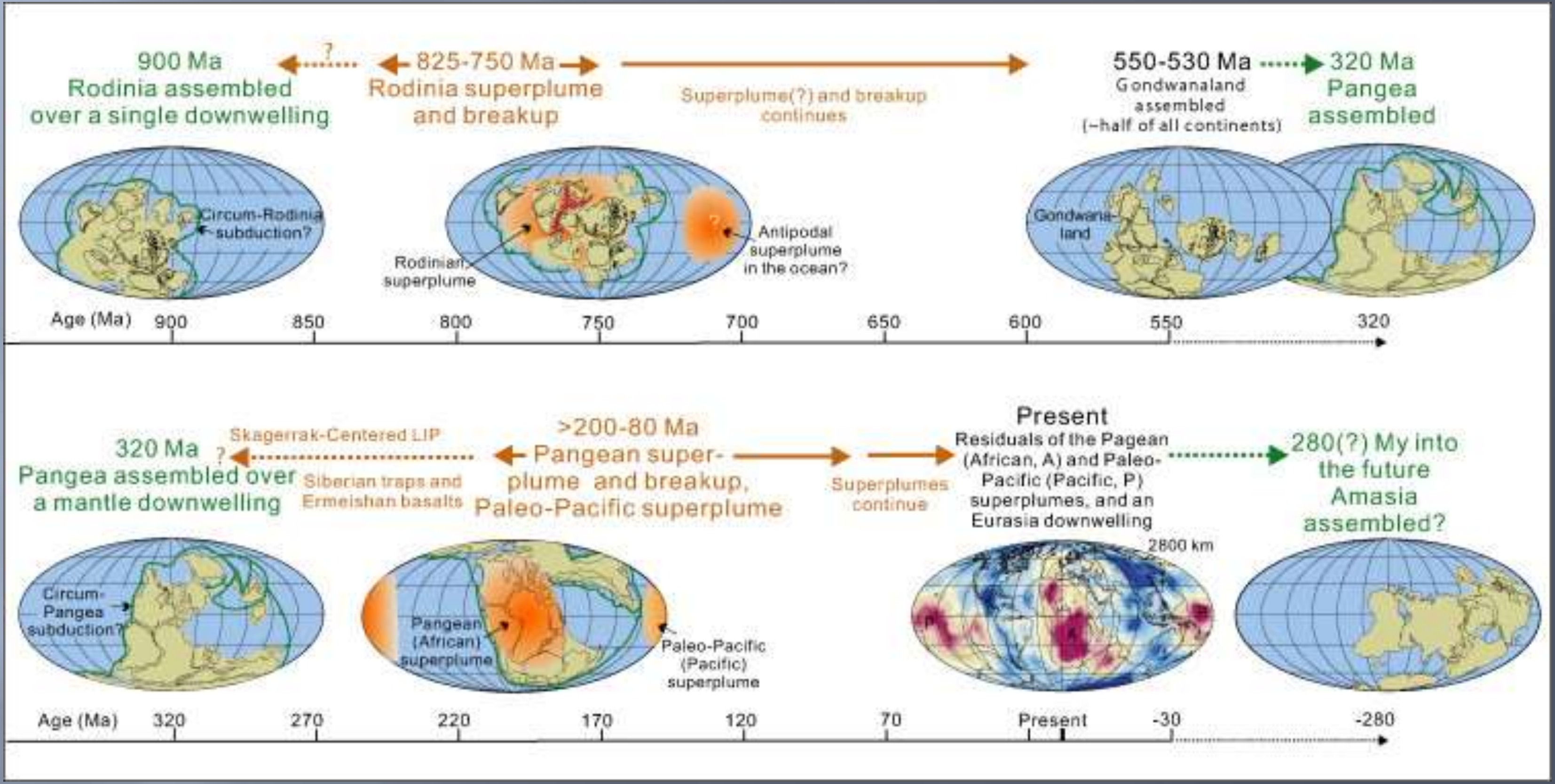
4. **The small or zero subsidence** – in several islands there are marine structures and deposits of different ages up to several million years old that appear to have remained close to present-day sea level.

Canarische eilanden



[Giovanni Bertotti
Leidse Winterlezing
12-2017]
http://rijnland.gea-geologie.nl/goudmijn

Canarische eilanden



[Giovanni Bertotti
Leidse Winterlezing
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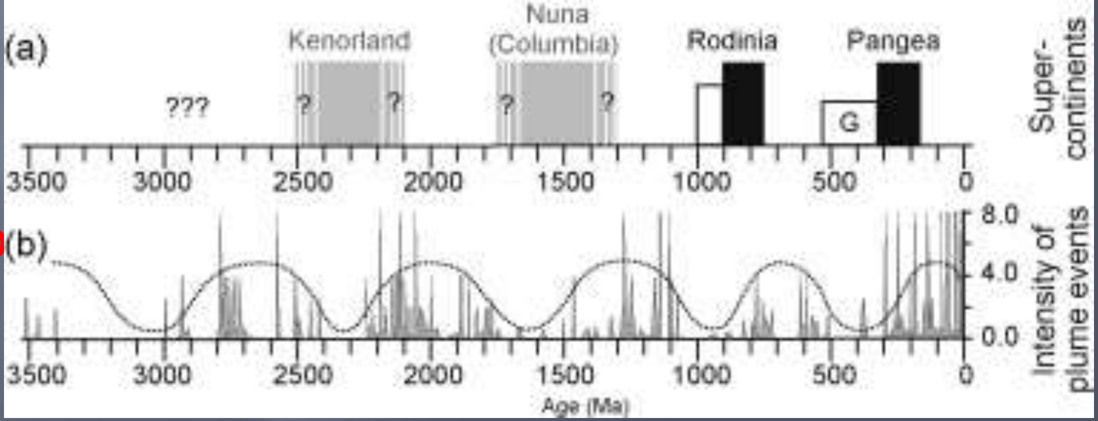
http://rijnland.gea-geo



500-
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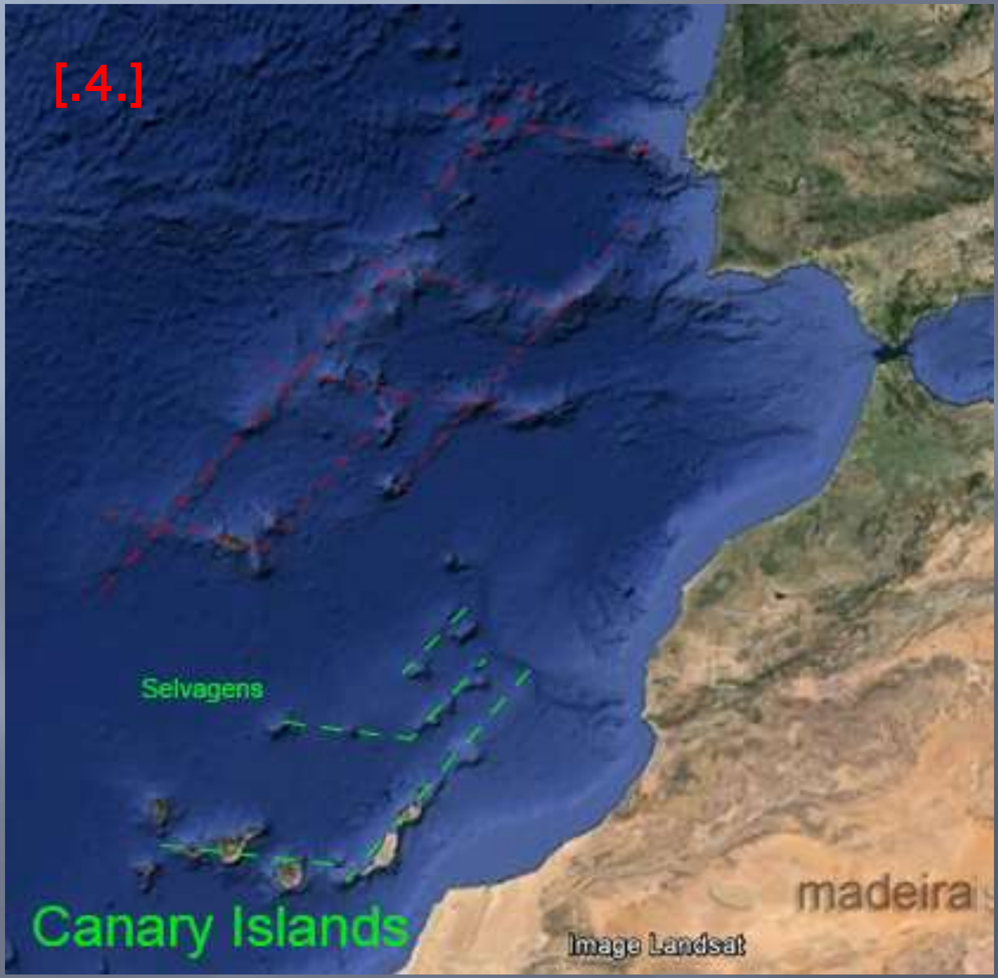
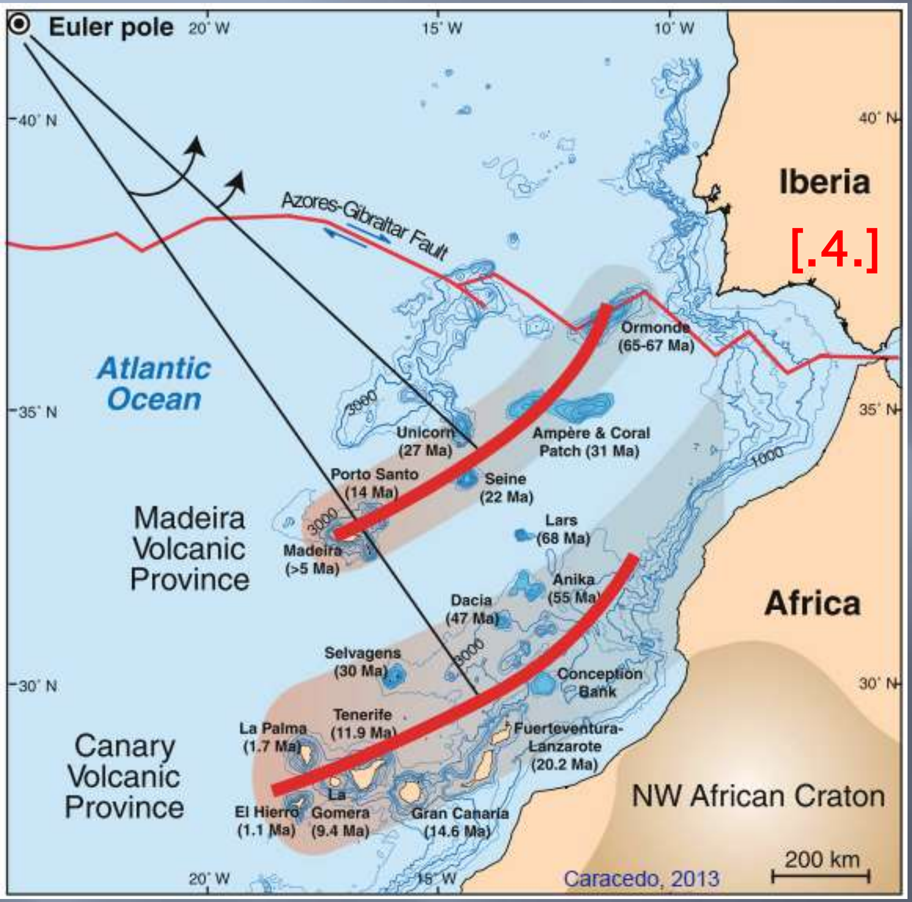
Canarische eilanden

Ontstaan: a.g.v. een hotspot??????



Bij de Canarische eilanden zien we twee lijnen die dezelfde orientatie hebben als bij Madeira. Een duidelijke W-E een lijn in de NE-SW richting. Werden de Canarische eilanden gevormd op oude breuken die voortkwamen uit de vroege periode van het openen van de Atlantische Oceaan???? Zelfs de Selvagens eilanden en de NE Onderzeese Bergen lijken dit “breukenpatroon” te laten zien. Critici zeggen dat er geen bewijs is voor het een dergelijke breuk. [.14.].

Canarische eilanden



Ontstaan: a.g.v. een hotspot??????

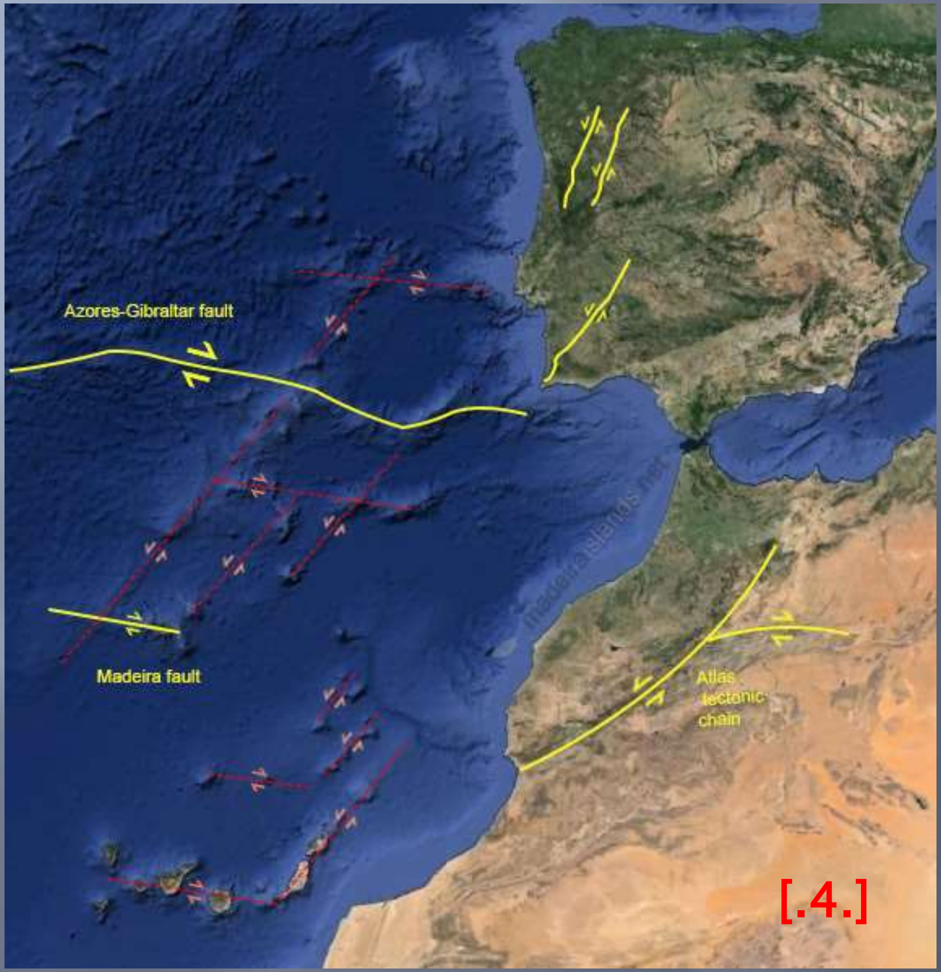
The hotspot of Canary Islands

Remember that if the plume concept is correct, all hotspot tracks on a single, moving plate should have a similar configuration (assuming the plate behaves like a rigid body). In the image you can see that an effort was made by the author to make the configuration of the Canary hotspot track similar to the Madeira one. But, as you can see it is far from fitting to the the actual alignment of the Canary islands:

As we have seen before the supposed hotspot track of Madeira does not seem to fit to what the seafloor tell us. And as we can see now the supposed Madeira and Canarias hotspot tracks does not seem to fit together either

Canarische eilanden

Ontstaan: a.g.v. een hotspot??????



Hoe gedroegen de breuken zich ten tijden van de vorming van de eilanden. Madeira: -5 Ma, Porto Santo Island: -14 Ma, Selvagens Islands: -27, and Canarische eilanden: -25 Ma.

Stel dat de eilanden zijn gevormd onder invloed van de Alpine Orogeny. De strike slip beweging tijdens het Cenozoicum in de Azores-Gibraltar breuk was dextral (met de klok mee). Hetzelfde geldt voor de grote breuk in Madeira (dextral). Breuken in de Atlas zijn sinistral (tegen de klok in) in de NE-SW richting, en dextral in de Hoge Atlas regio. Other NE-SW faults are sinistral under the Alpine convergence.

Canarische eilanden

[.50. (Duggen)]

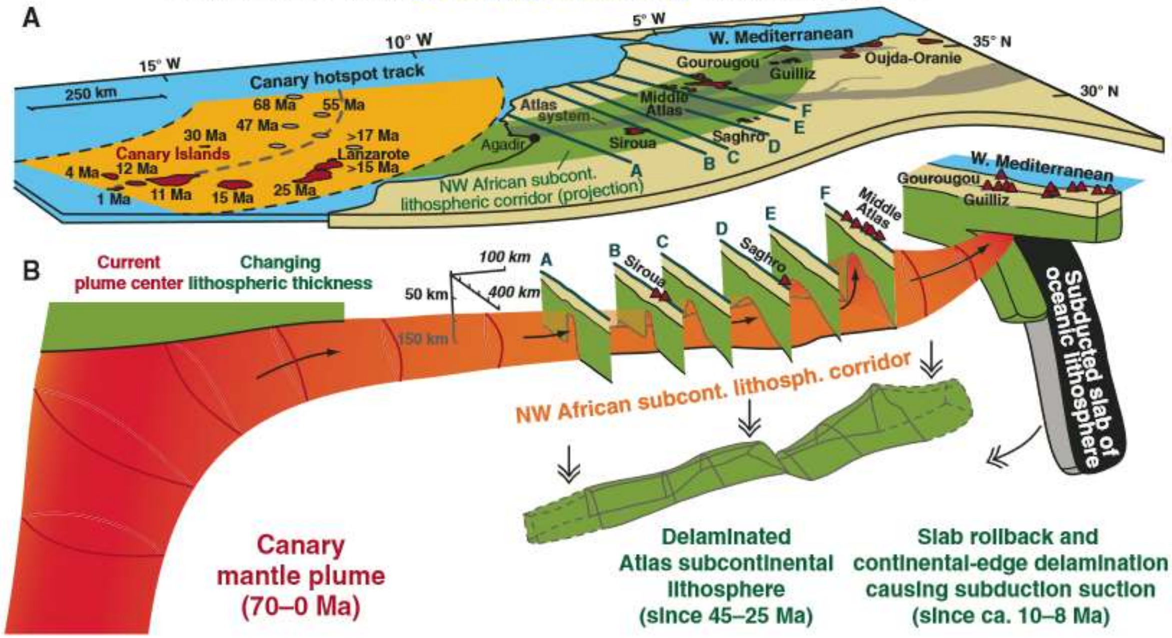


Figure 1. Map of the northwest African plate (A) and flow of Canary mantle plume material under northwest Africa through a subcontinental lithospheric corridor in a three-dimensional model (B). A: The orange area displays the Canary hotspot track on the oceanic side of the northwest African plate with ages of the oldest lavas from each island (red areas) or seamount (gray circles), indicating a southwest-directed age progression and the location of the current plume center beneath the western Canary Islands (Geldmacher et al., 2005). Also shown are the Atlas Mountains (gray field), location of the northwest African subcontinental lithospheric corridor in green, inferred from profiles (A–F) based on geophysical data (Urchulutegui et al., 2006; Missenard et al., 2006; Teixell et al., 2005), and northwest African Neogene continental intraplate volcanic fields. B: The three-dimensional model illustrates how Canary mantle plume material flows along the base of the oceanic lithosphere that thins to the east (Neumann et al., 1995) and into the subcontinental lithospheric corridor beneath the Atlas system, reaching the western Mediterranean. Plume push, eastward-thinning lithosphere, delamination of northwest African subcontinental lithosphere, and subduction suction related to rollback of the subducting slab in the Mediterranean are proposed to be the main mechanisms for causing Canary plume material to flow ≥1500 km to the northeast.

Ontstaan: a.g.v. een hotspot??????

Geldmacher (2005): “The role of mantle plumes in the formation of intraplate volcanic islands and seamount chains is being increasingly questioned.”

Selvagens eilanden

[.29.]

Selvagens eilanden

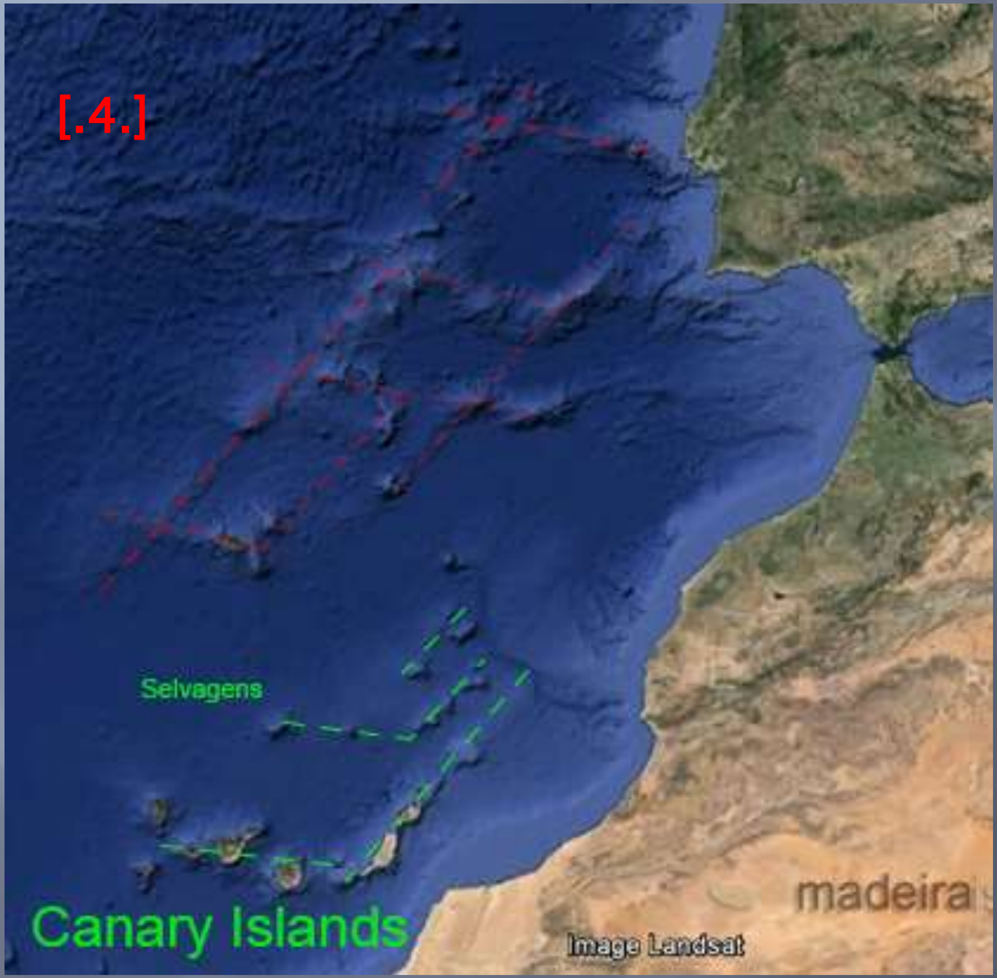
The islands are considered to be a ***column branch*** that extends from Canary Islands at a 3,000 m depth.

The islands' physical characteristics are the consequences of mountain-forming and volcanic forces that occurred between 60 and 70 million years ago, typical of many of the islands of Macaronesia. The islands were created during the late Miocene period (-26 Ma), from a large submarine volcano and shaped by erosion and marine sedimentation.

They were never connected to the African continent.
The islands themselves are crossed by many calcareous faults, some marbleized, and made of basaltic rock, ash, and other volcanic materials.

Steeds worden hotspots genoemd als starters.
Het lijkt veel “kopie” praat.

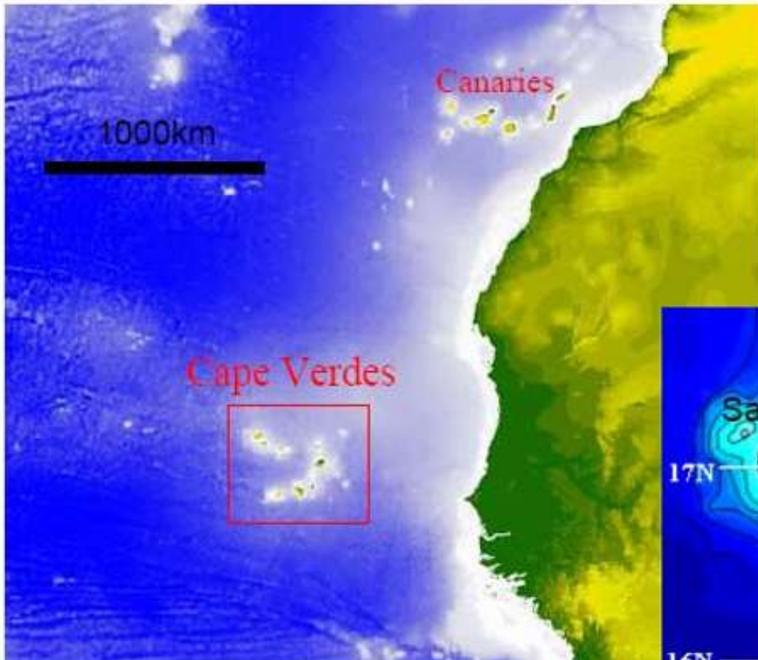
Selvagens eilanden



Steeds worden hotspots genoemd als starters.
Het lijkt veel “kopie” praat.

En…. Kijk nog eens goed naar het plaatje hiernaast. Ook hier zijn er breuklijnen te volgen

Kaapverdische eilanden



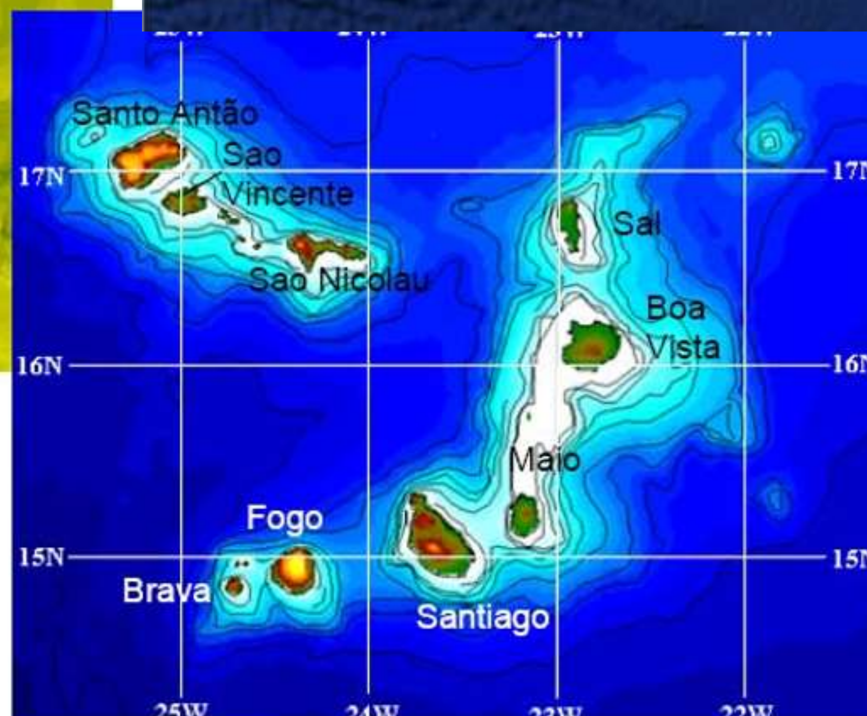


Figure 1: Location maps of the Cape Verde rise off the west coast of Africa and a 500m contour map showing the islands.

[.17.]

Kaapverdische eilanden

[.28.]

- 180 million years ago: The first seamount created at what is now Cape Verde, its location was at the Mid-Atlantic Ridge.
- 136 to 113 million years ago: The seamount that is now known as Maio started to form
- About 119 to 118 million years ago: Seamount now known as Santo Antão formed during the Aptian era
- 50 million years ago: The island now known as Sal was formed during the eruption of a volcano which is now inactive, the geologically oldest island in Cape Verde.
- About 20 million years ago: The seamount of Brava formed
- 100,000 to 50,000 years ago - The upper part of the Monte Gordo Formation on modern day São Nicolau formed

Kaapverdische eilanden

C. J. Stillman et al. [.16.] (1982)

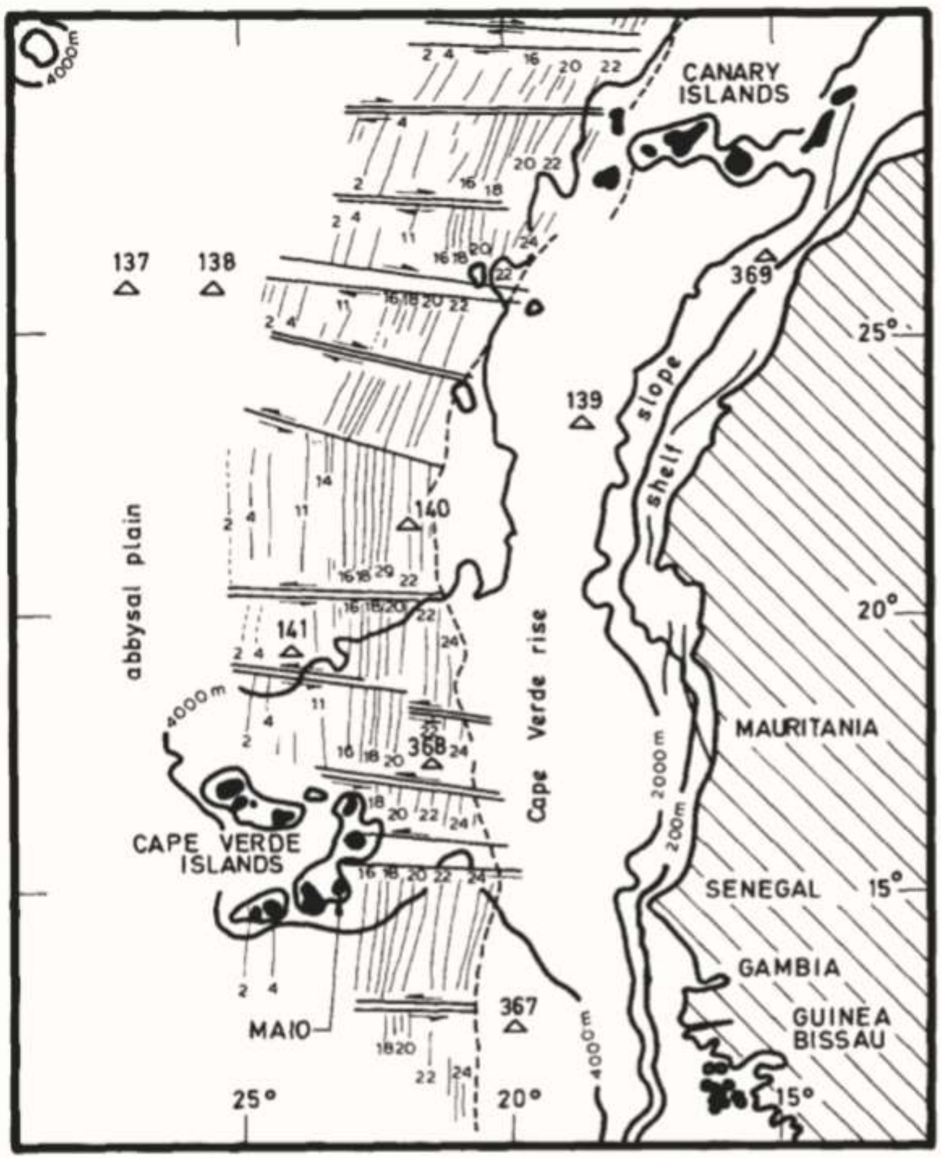


FIG. 1. Location map with bathymetry and magnetic anomalies of the Cape Verde–Canaries region of the Atlantic. Magnetic anomalies of the M-series after Hayes & Rabinowitz (1975). Numbered triangles: D.S.D.P. sites.

[.17.] (2007)

The origin of the island chains is believed to relate to volcanic activity from an underlying mantle plume. It has been surmised that the volcanoes are of late Tertiary origin, resting upon a Mesozoic-aged seafloor, with most of the islands having formed between 5 and 15 Ma on lithospheric of approximately 130 Ma age (McNutt, 1988).

Kaapverdische eilanden

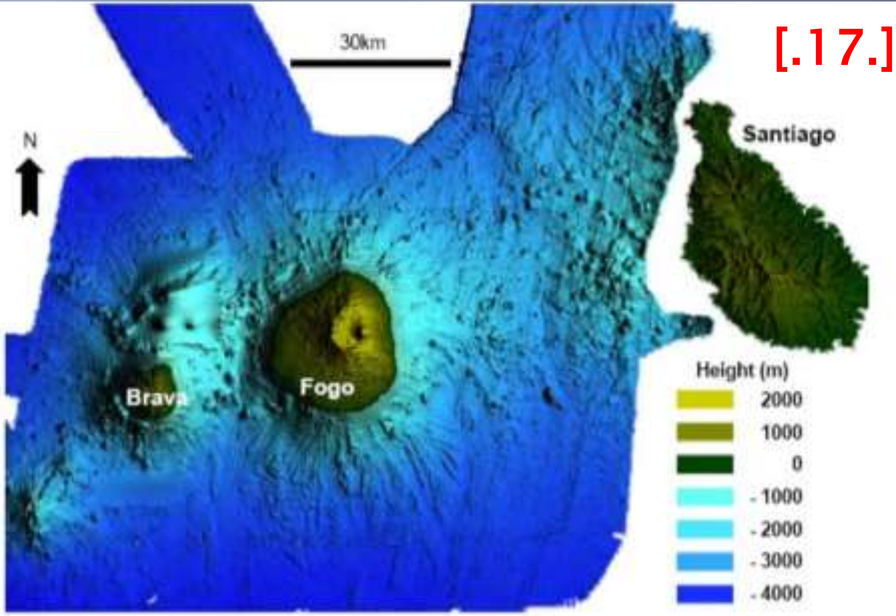


Figure 2: Topography of, and bathymetry around, the islands of Brava, Fogo and Santiago. Data compiled from Simrad EM12 and Atlas Hydrosweep bathymetry together with Shuttle Radar Topography Mission topography. The image is shown in shaded relief and shows many channels

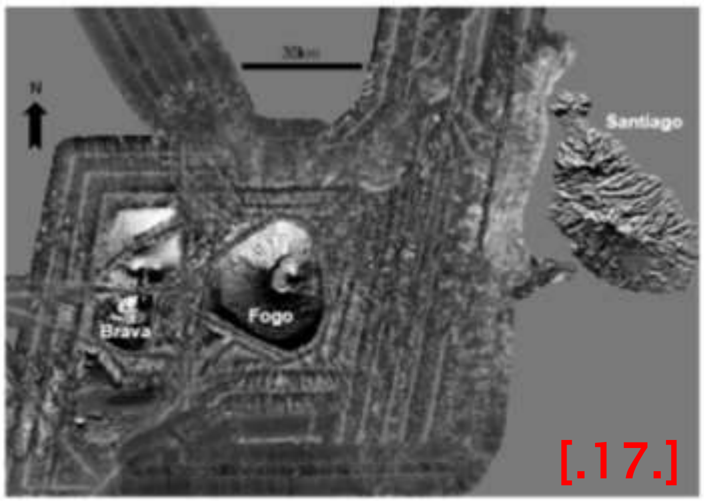


Figure 3: Multibeam backscatter imagery from the Simrad EM12 and Atlas Hydrosweep systems around the islands of Brava, Fogo and Santiago. Low backscatter is shown as dark and high as white. Level of backscatter is used as a measure of seafloor roughness and grainsize. A combination of morphology and backscatter imagery is used to interpret process related features, such as individual debris avalanches or debris flows.

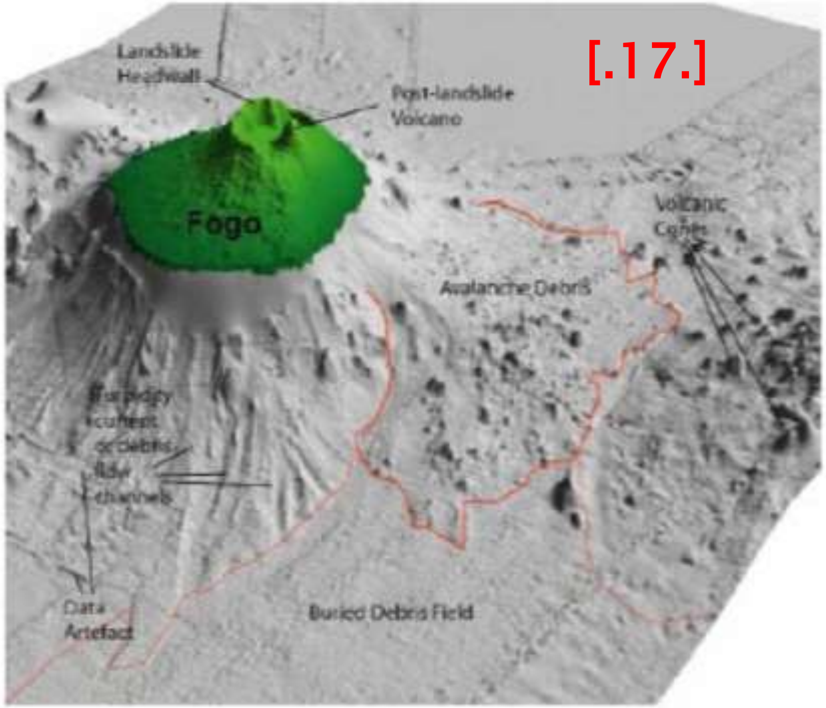


Figure 6: Three-dimensional model showing the seafloor to the east of the Island of Fogo. It shows the debris avalanche deposits, volcanic cones and debris flow channels interpreted from the bathymetry, backscatter and slope analysis data.

[.19.] (2003)

Kaapverdische eilanden

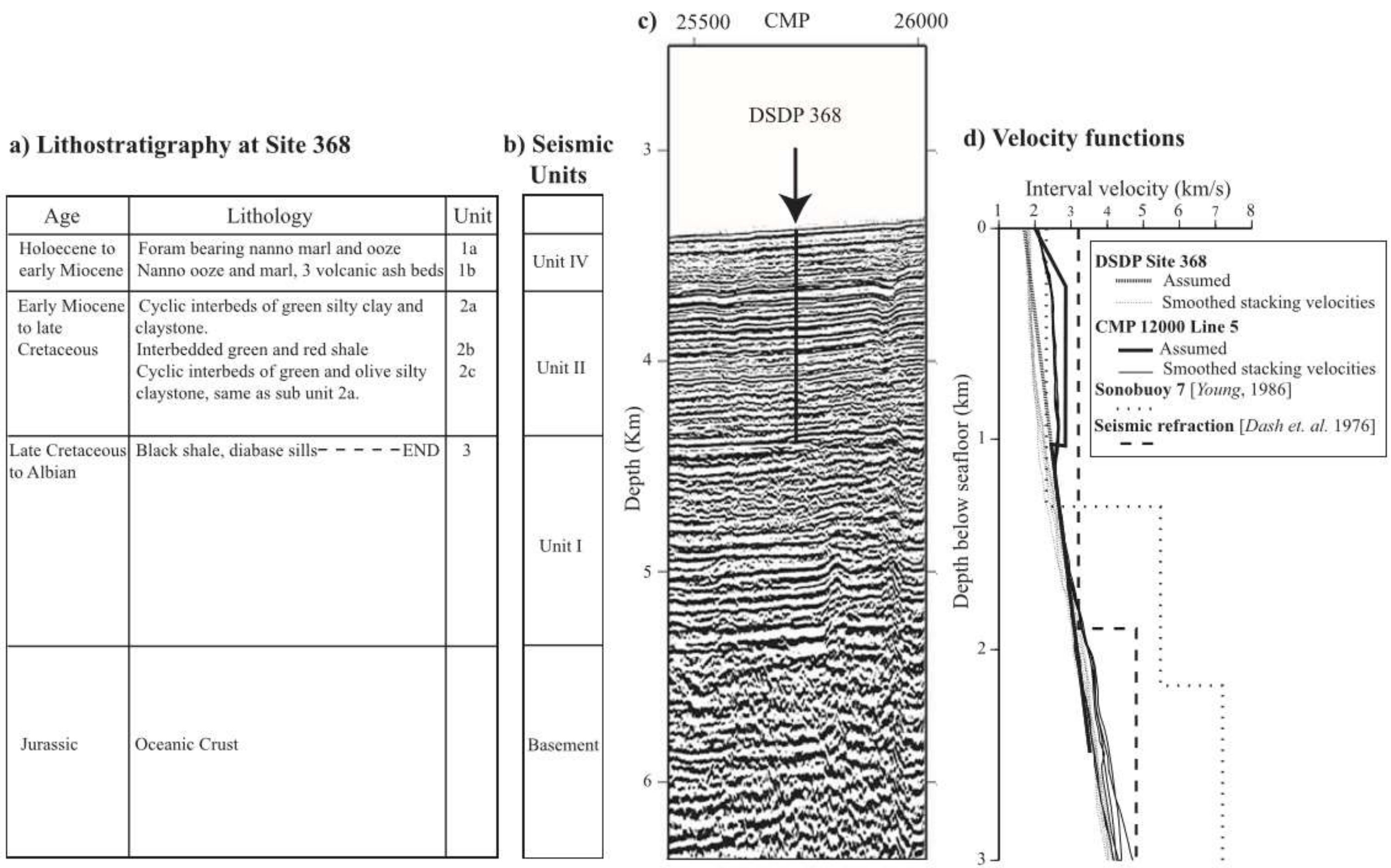


Figure 2. Summary stratigraphy and seismic units at Deep-Sea Drilling Project (DSDP) Site 368. (a) Summary stratigraphy [*Lancelot et al.*, 1978]. (b) Seismic units. Note the absence of unit III (see text for discussion). (c) Seismic line 1 (CMPs 25500–26000) and the projected position of Site 368. (d) Velocity functions derived from semblance, sonobuoy 7, and the seismic refraction experiment of *Dash et al.* [1976].

[.19.] (2003)

Kaapverdische eilanden

Units	Reflector characteristics and geometry	Typical seismic data	Interpretation
IV	Uppermost reflector, high reflectivity, parallel seafloor, not as many reflectors as other units and laterally continuous.		Pliocene to recent
III	Bright laterally continous reflectors, wedge shape, onlap at base. Basal unconformity marked by a high amplitude reflection.		Early Miocene to late Miocene? Moat infill
II	High reflectivity and generally laterally continuous reflections with some low amplitude intervals.		Late Cretaceous to late Oligocene Margin sediments
I	High reflectivity, reflector geometry controlled by underlying basement.		Jurassic to Early Cretaceous Margin sediments
Basement	High reflectivity and irregular high amplitude reflection at top.		Jurassic/Early Cretaceous oceanic crust

Figure 5. Summary of the main seismic units showing reflector character, seismic facies, and geological interpretation.

[.19.] (2003)

Kaapverdische eilanden

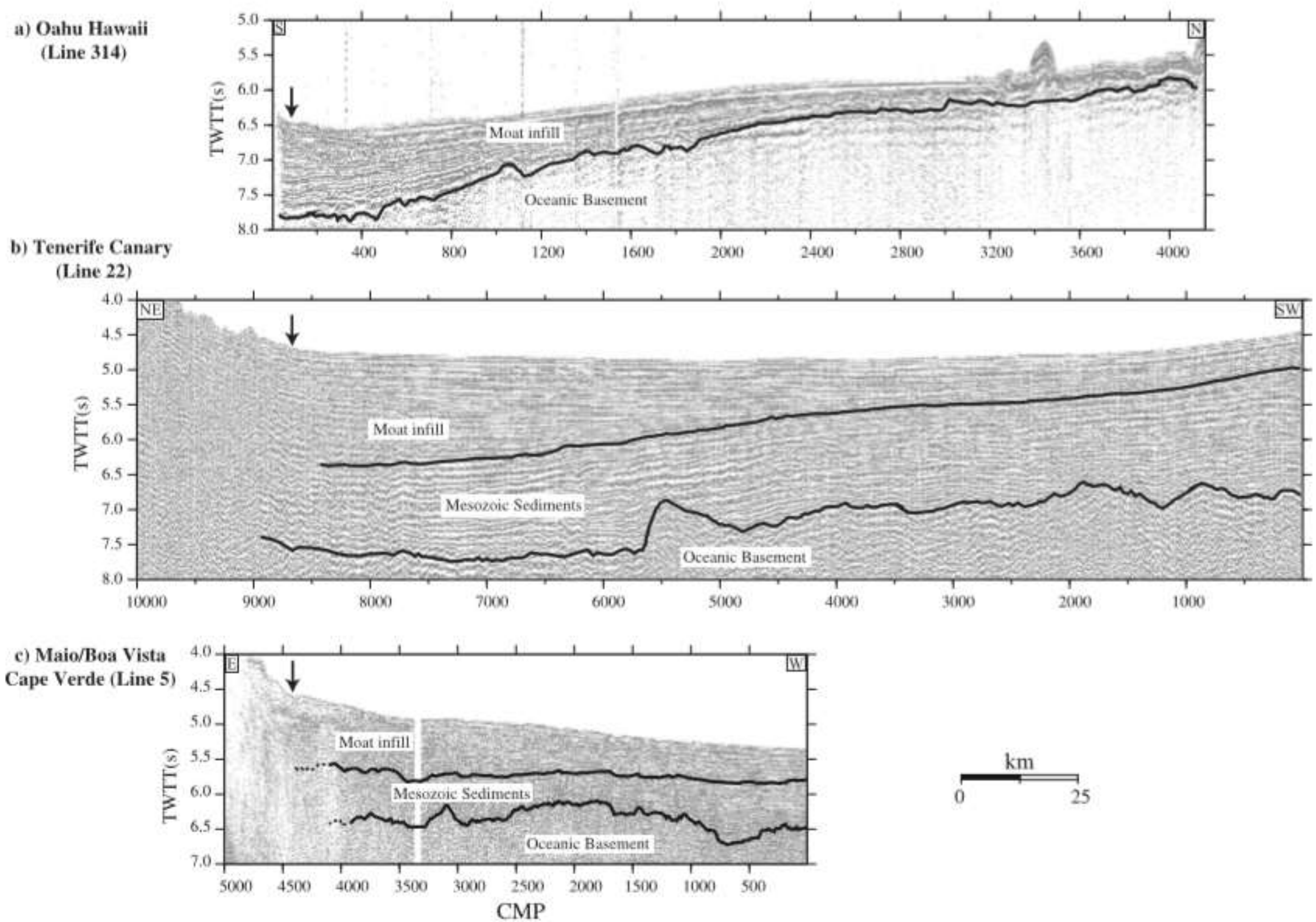


Figure 8. Comparison of (c) seismic reflection profile line 5 of the west flank of Boa Vista with (a) line 314 of the Hawaiian Islands flexural northeast of Oahu [*Watts et al.*, 1985] and (b) line 22 of the Canary Islands flexural moat south of La Gomera [*Watts et al.*, 1997]. The Cape Verde Islands moat infill is tilted away from the islands, unlike Hawaii and Canary Islands, where the sequences dip toward the islands.

Kaapverdische eilanden

[.19.] (2003)

Van de conclusies:

3. The Cape Verde flexural moat cannot be explained only by surface loading unless Te values that are well in excess of the expected value for 140 Ma oceanic lithosphere are assumed. The problem is that the predicted flexure is too large in amplitude and too short in wavelength compared to the observed. (T: travel time)

9. The origin of the Cape Verde swell is not known. However, a Te, that is normal for the load and plate age, together with a modest heat flow anomaly, suggest that the swell cannot be explained only by uplift due to thermal reheating of the lithosphere by an underlying hot spot and that other, deep-seated, mantle processes must be involved.

Kaapverdische eilanden

[.21.] (2007) Shallow-water limestones of presumed Late Cretaceous and Eocene age, interbedded with basaltic lavas, were described by earlier authors from São Nicolau in the northwestern part of the Cabo Verde archipelago. If confirmed, these ages would imply late Mesozoic shallow-marine and subaerial volcanic activity in the Cabo Verde archipelago, and document a geological history very different from that known so far from other Cabo Verde Islands, from which no subaerial volcanic activity before the mid-Cenozoic is known. Our re-investigation of the foraminiferal fauna indicates a Late Miocene age for the presumed Late Cretaceous and Eocene limestones.

The hypothesis of a long-lived hot spot, active by the Early Cretaceous, and of a major island-building stage in the Cabo Verde Islands during this period, is therefore not supported by the present bio- or chronostratigraphic data.

Kaapverdische eilanden

[.22.] (2006) Only abstract

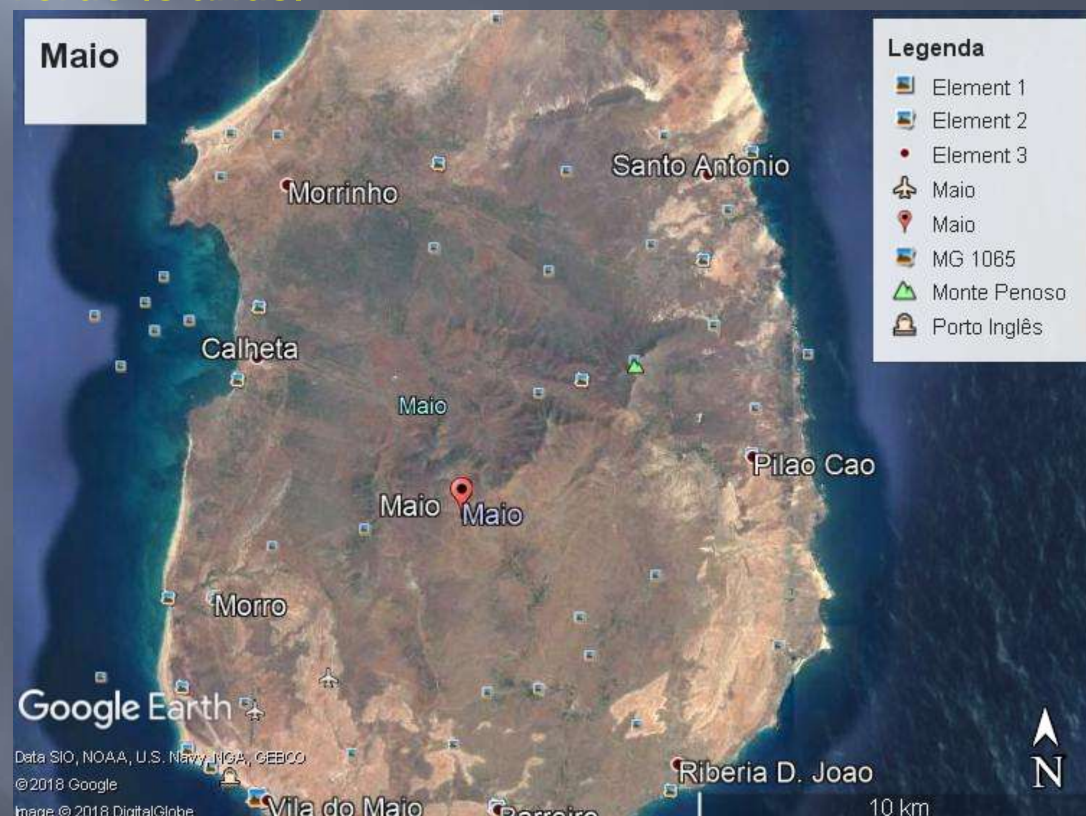
The hotspot swell---an area of uplifted bathymetry or topography surrounding regional volcanism---is a defining hotspot characteristic, yet its origin is poorly understood. To test current ideas about swell formation, we studied the crust and shallow mantle structure of the Cape Verdes in a passive seismic experiment……………….

Here we present an analysis of compressional to shear (P to S) converted seismic phases, recorded on a temporary network of seismograph stations on the Cape Verde Islands, that indicate a crust thickened to 22 km is underlain by a high-velocity, low-density layer, which overlies a zone of low shear-wave velocity starting at ˜80 km depth. We also measured shear-wave splitting delay times for teleseismic SKS phases, which are ˜0.81 s, compatible with an origin in this same layer. We interpret these observations **as effects of hotspot melting,** which produces a thickened crust and a depleted swell root that buoys the ocean floor and spreads laterally as it grows over time.

Kaapverdische eilanden

[.23.] (1971) The Cape Verde Islands rise from an abyssal plain with depths of more than 4,000 m and are all of volcanic origin with volcanism still active on some islands. The importance of the archipelago in connexion with the evolution of the Atlantic Ocean is largely provided by the geology of Maio, one of the smaller islands of the group. When the ocean opened, limestones were deposited in this area and the structure of the island seems to indicate that a volcanic ridge with north-south trend was formed at the site of the Cape Verde Islands.

Beach on São Vicente Island.



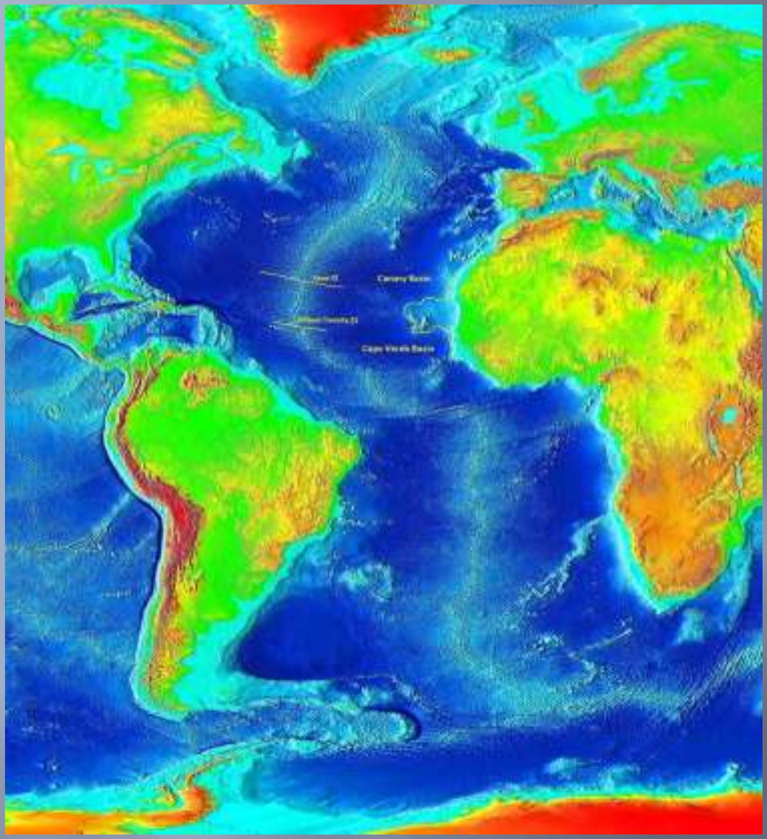
Kaapverdische eilanden

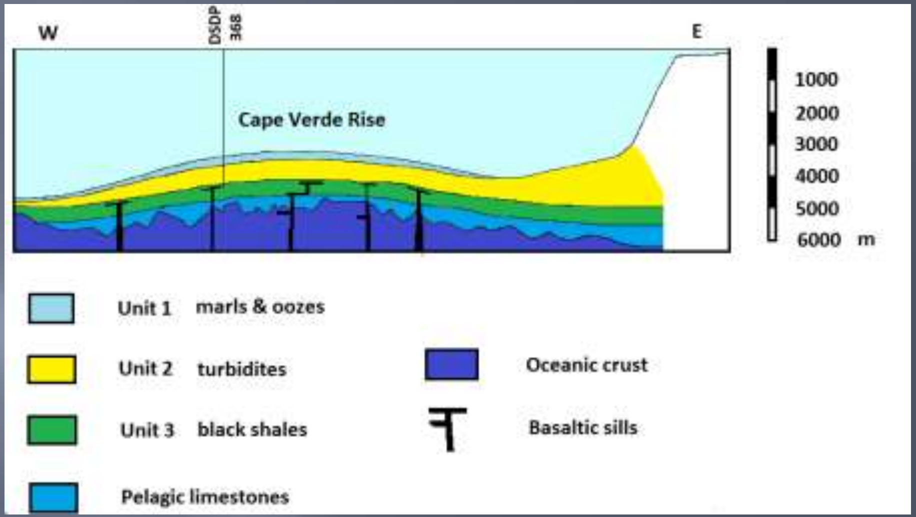
[.26.] (1990) Accurate locations have been made for 13 fracture zones across the Cape Verde Rise and four previously unknown fracture zones mapped. Evidence for their existence is from analysis of the M series of magnetic anomalies together with evidence from seismic reflection profiles where these data exist. The Cape Verde Islands themselves lie among a series of five fracture zones. **The continuity of magnetic lineations and fracture zones across the region of the Cape Verde Islands indicates not only that the islands lie on oceanic crust but also that the original Mesozoic seafloor features and magnetization persist and were not obliterated by the Neogene reheating, uplift and volcanism.**

[.25.] (2006) Either due to tectonic or any other process the scale of the basement bulge is comparable to that of terrestrial mountains ranges. Additionally, this range is not isolated in the Eastern Central Atlantic region, the Tore-Madeira rise and Meteor rise are of very similar scale and could have been formed around the same period. All this suggests to consider the geological history of the Canary and Cape Verde Islands as part of that of the Eastern Central Atlantic ocean as a whole.

[.3.] **The Tore-Madeira Ridge**, a bathymetric structure along a N-NE to S-SW axis that extends for 1,000 km. This submarine structure consists of long geomorphological relief; its highest submersed point is at a depth of about 150 m. The origins of the Tore-Madeira Ridge are not clearly established, but may have resulted from a morphological ***buckling*** of the lithosphere.

Kaapverdische eilanden





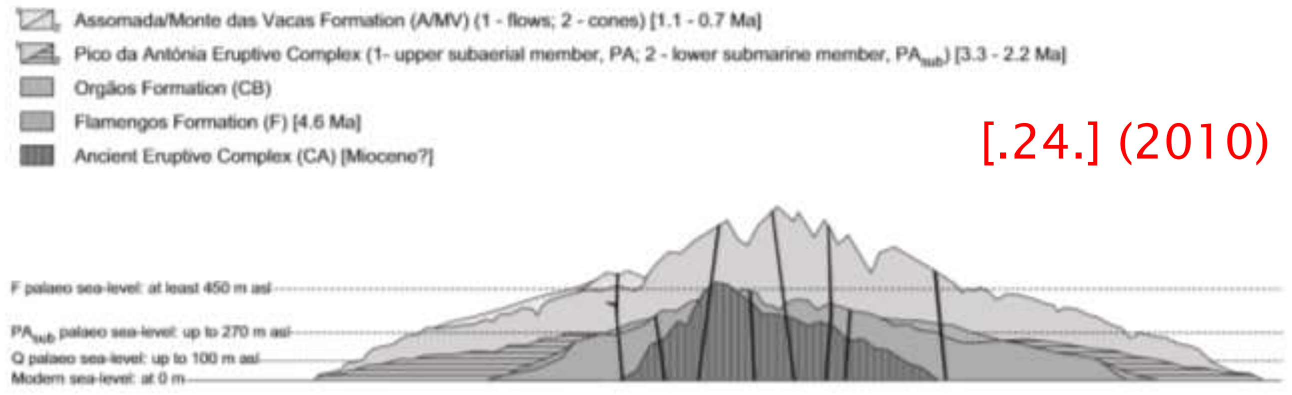
By Rudolf Pohl - Own work, CC BY-SA 3.0, https://commons.wikimedia.org/w/index.php?curid=18960072

[.27.] (1990) The rise are bounded by the Canary Basin to the north and the Cape Verde Basin to the south Numerous seamounts are located in the rise including the Cape Verde

In the rise there are 13 smaller fracture zones, three extends as far as the Cape Verde Basin and another extends north into the Canary Basin and within the Canary Islands.

[.24.] (2010)

Kaapverdische eilanden

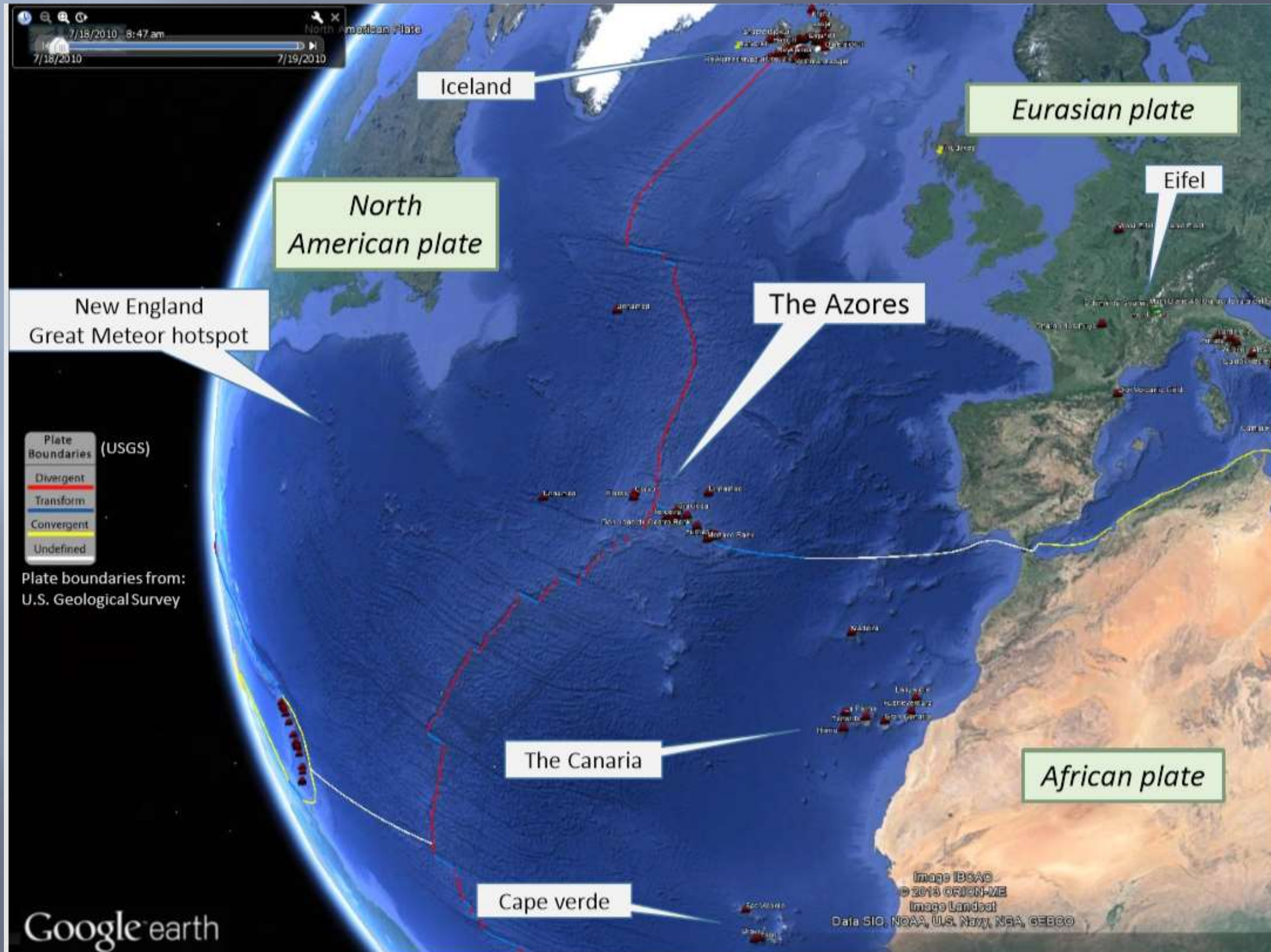


[.24.] (2010)

Figure S5: Idealized cross section of Santiago showing the geometric relations between the units, and the information of relative past sea-levels inferred from the volcanostratigraphy. Note the increase in elevation with increasing age. Stratigraphic units after Serralheiro (1976), and the geochronology after Holm *et al.* (2008).

Thus, differential uplift may eventually be partially explained by differential subsurface loading: different amounts of local underplating or intrusions at the base of each edifice can generate uneven upward buoyancy conditions that result in differential uplift. In fact, the existence of differential crustal thickening was inferred by Lodge & Helffrich (2006) using receiver function analysis, supporting the possibility of subsurface loading restricted to the vicinities of each island edifice. **However, a direct relationship between the amount of crustal thickening** inferred by Lodge & Helffrich (2006) **and the amount of uplift we infer is not immediately evident** (e.g. the crust underlying Santo Antao and Sao Nicolau exhibits similar thickening but the islands exhibit very different uplift trends).

De Azoren



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Iceland
Eurasian plate
Eifel
North
American plate
New England
Great Meteor hotspot
The Azores
Plate Boundaries
(USGS)
Divergent
Transform
Convergent
Undefined
Plate boundaries from:
U.S. Geological Survey
The Canaria
African plate
Cape verde
Google earth
Data SIO, NOAA, U.S. Navy, NGA, GEBCO

De Azoren

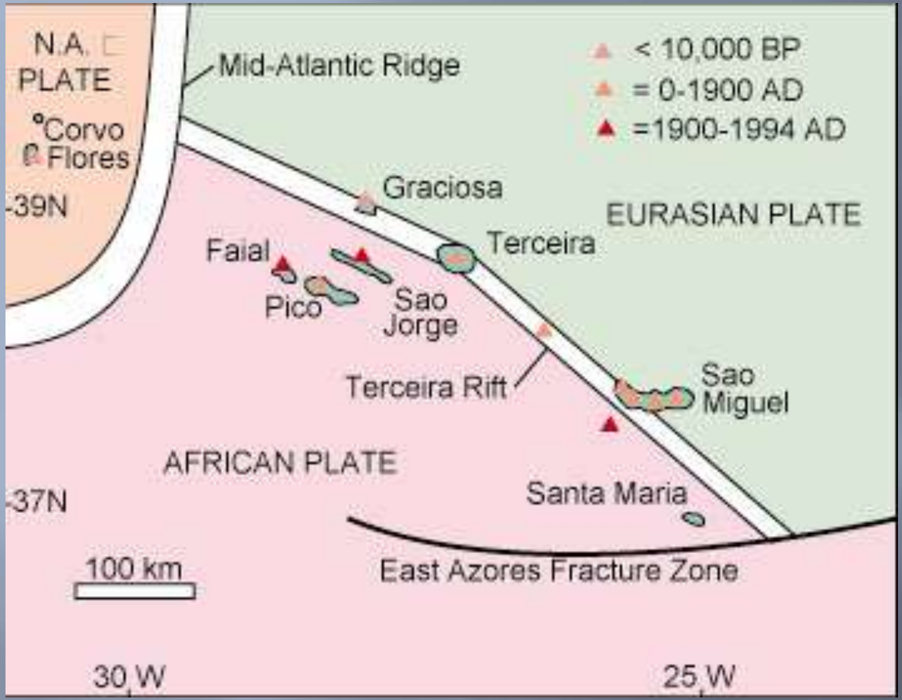
Vanwege de kolonisten uit het graafschap Vlaanderen die in de vijftiende eeuw voor het bevolken van de eilanden werden aangetrokken, werden ze tot in de zeventiende eeuw ook wel Vlaamse eilanden genoemd, alhoewel de eilanden altijd Portugees gebleven zijn

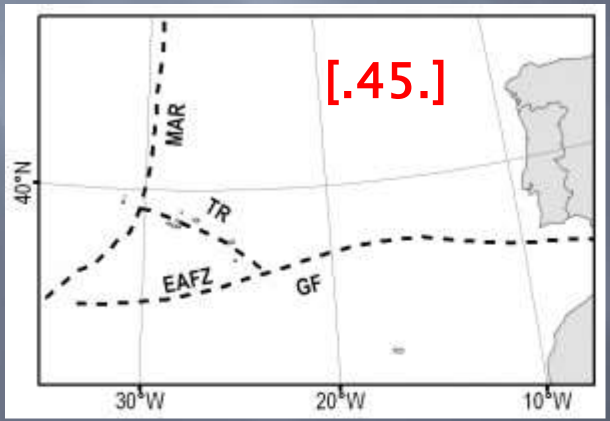
[.31.] (2006+)

The Azores archipel is the result of the volcanic activity associated with the triple junction where the American, Eurasian and African litospheric plates meet. The MidAtlantic ridge (MAR) separates the American from the Eurasian and Africa plates. The Azores-Gibraltar fracture zone marks the boundary between Eurasia and Africa.
The islands emerge from the Azores volcanic plateau, which is a first-order morphological feature in the Atlantic basin. It has an overall triangular shape.

[.44.] (1994+)

De Azoren





The Azores are shown as hot spot volcanoes on some maps but physical and chemical evidence shows they are associated with a spreading center. Searle showed that the third leg is the Azores spreading center. This spreading center (called the Terceira Rift) is made of a series of en echelon rifted basins. The spreading center formed about 36 million years ago and has been migrating to the south. The Azores lack a linear progression in the age of the volcanoes, a trend common in volcanoes associated with hot spots. Map modified after Moore (1990).

De Azoren

[.31.]

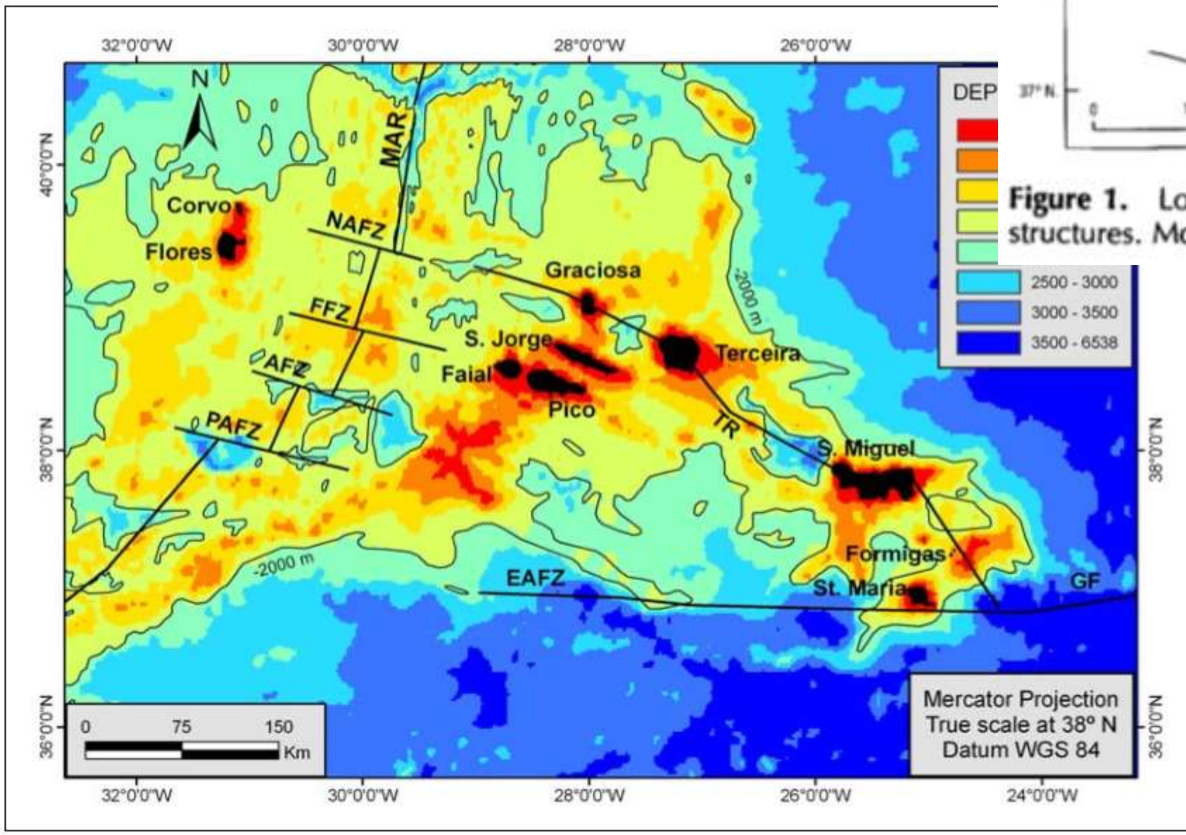


Figure 18 – Tectonic setting of the Azores archipelago (MAR modified from Luis et al., 1994; SJLT modified from Vogt and Jung, 2004). AFZ= Açor Fracture Zone; EAFZ= East Azores Fracture Zone; FFZ= Faial Fracture Zone; GF= Gloria Fault; MAR= Mid-Atlantic ridge; NAFZ= North Azores Fracture Zone; PAFZ= Princesa Alice Fracture Zone; TR= Terceira Rift. Bathymetry of the Azores archipelago from GEBCO (IOC IHO and BODC, 2003).

[.32.]

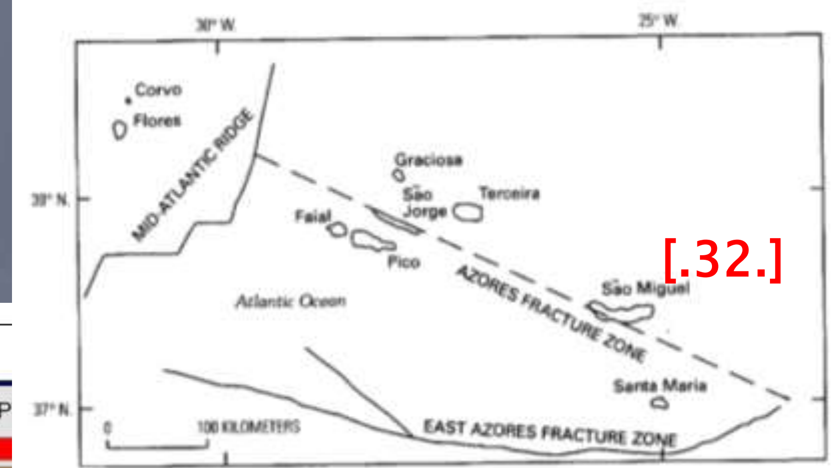


Figure 1. Location of Azores fracture zone and other major structures. Modified from Laughton and Whitmarsh (1975).

[.34.]

Fig. 1: Location of the Azores archipelago (Morton, B., et. al., 1998).

De Azoren

[.31.] (2006+)

Recently, various works, based on bathymetric (Lourenço et al., 1998), gravity (Luis et al., 1998), and seismic (Miranda et al., 1998) data have proposed a new model for the Azores Plateau region (Figure 19). These authors state that, presently, this region is a narrow diffuse plate boundary consisting of several tectonic blocks limited by two sets of conjugated faults striking 120º and 150º. These faults established the framework for the onset of volcanism, expressing as linear volcanic ridges or as point source volcanism. This area acts simultaneously as an oblique ultra slow spreading center and as a transfer zone that accommodates the differential shear movement between the Eurasian and African plates from the MAR until the western tip of the Gloria fault.

More recently, Fernandes et al. (2004; 2006) using new geodetic data revealed that Faial, Pico, S. Jorge, Terceira and S. Miguel Islands are clearly in the deformation zone whilst Graciosa Island belongs to the stable Eurasian plate and Santa Maria Island to the African plate.

De Azoren

São Miguel

[.42.]

[.34.] (2010)

These nine islands are divided in three groups – the Oriental group, with Santa Maria and São Miguel; the Central group, with Terceira, Graciosa, São Jorge, Pico e Faial; and the Ocidental group with Flores and Corvo. According with Morton et al., 1998, the first two groups are located mainly in Azores microplate and the last group in American plate.

Santa Maria (Filipe Jorge, 2000)

The three (sleepy) volcanos are – Água de Pau, Sete Cidades with two lagoons inside, Green and Blue lagoon, and Furnas with hydrothermal waters.

São Miguel coast zone (F. Taveira Pinto, 2002)

De Azoren

De vuurtoren die eerst aan de westkust stond, stond na de eruptie tegen een berg aan (1958).

Faial, Capelinhos volcano 1957/58 (Filipe Jorge, 2000)

Flores en Corvo op de Amerikaanse plaat (Filipe Jorge, 2000)

De Azoren

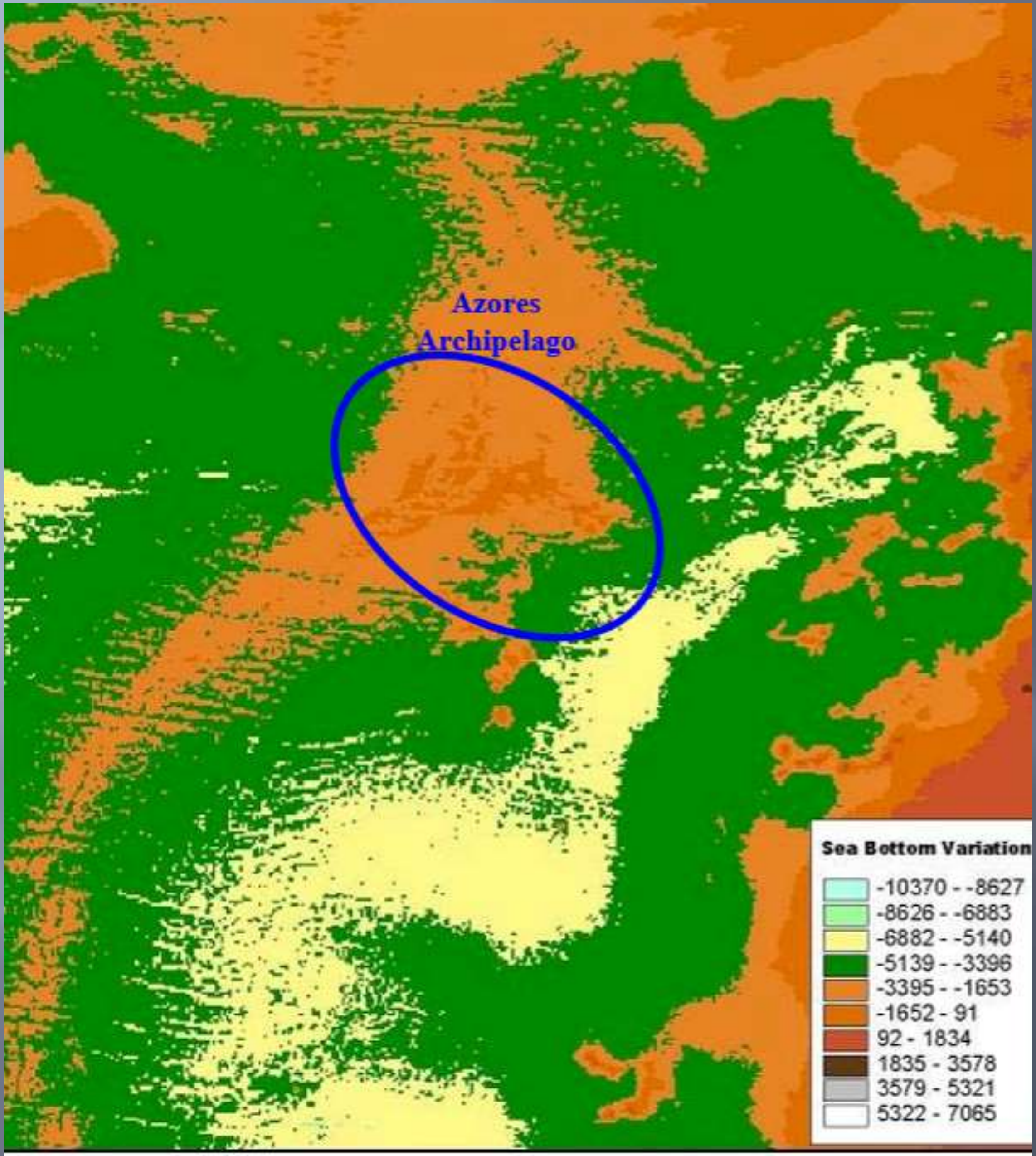


Fig. 18: Study area bathymetry (based on Large Marine Ecosystem).[.34.]

De Azoren

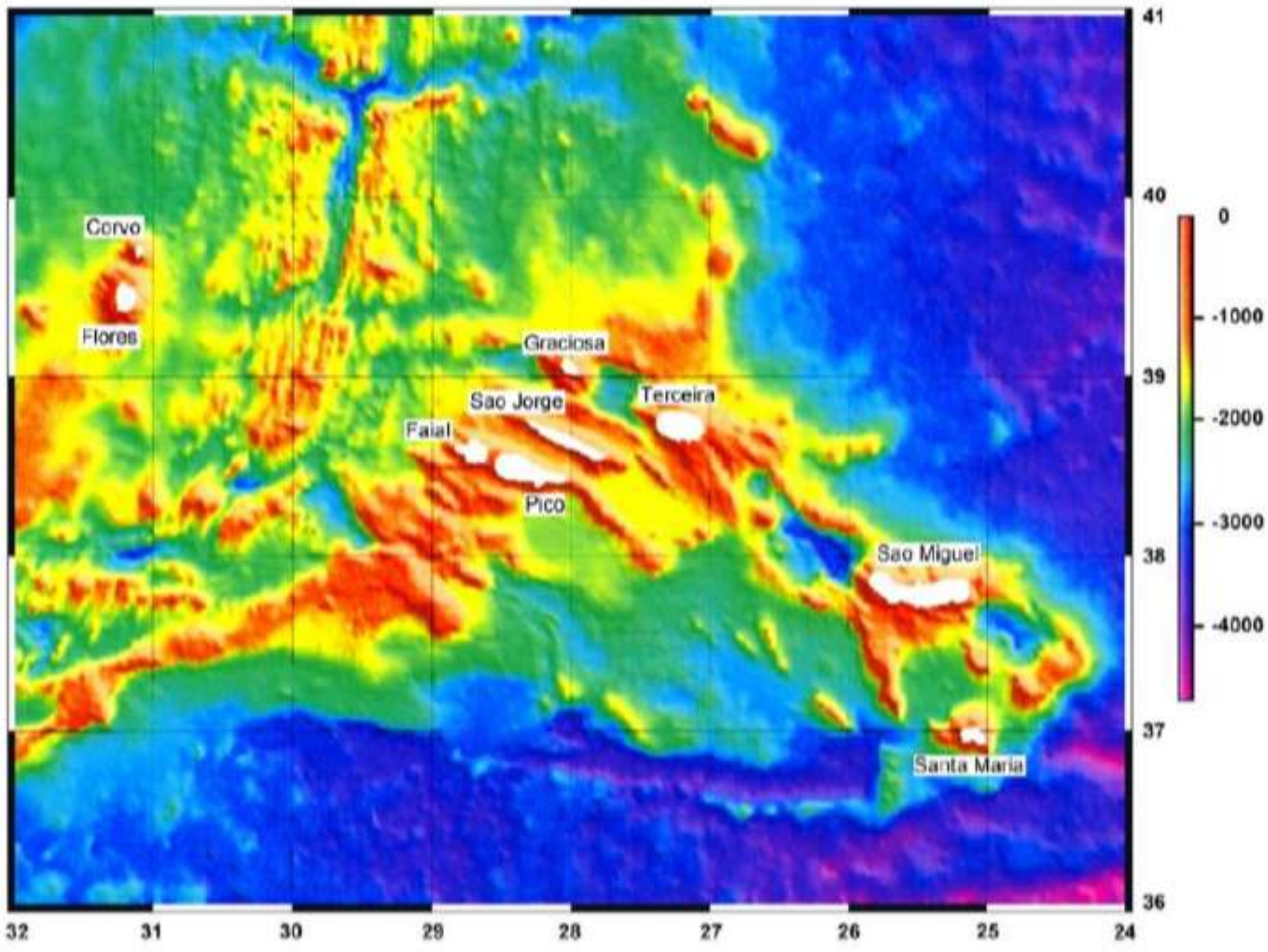


Fig. 1. Bathymetry of the Azores Plateau and location map of the nine islands of the Azores archipelago (Lourenço et al., 1998).

(Quartau, 2007; Babtisteet al, 2009)

[.34.]

Azores is a hotspot yes.... But is it a mantle plume ?

De Azoren

Hotspot

- Intense volcanism
- High heat flow
- High topography
- Sometimes trail

Hotspot is something you can see on the earth's surface.

Mantle plume

- Plume of solid, but hotter material rising by buoyancy from depth in the mantle
- Melt formed near the surface, feeds volcanoes of hotspot

Mantle plume is something you can only see deep in the mantle.

(Páll Einarsson, presentation 2012 in Current crustal)

Hypotheses proposed for the plateau formation

Tectonic origin

- The enhanced upwelling and magmatism driven by plate-boundary forces.
- The northward jump of the triple junction that this mechanism is a result of small changes in the relative motion between the three megaplates (Luis et al 1994)

Mantle plume origin

- Other (Yang et al, 2006; Vogt and Jung, 2004) assume a mantle plume is necessary to explain the plateau formation.
- The northward jump of the triple junction is then a result of relative motion of the plates and the mantle plum.
- For Gente et al. (2003), the plateau results from the interaction between the MAR and the plume, followed by the progressive southward rifting of the plateau after 7 Ma.

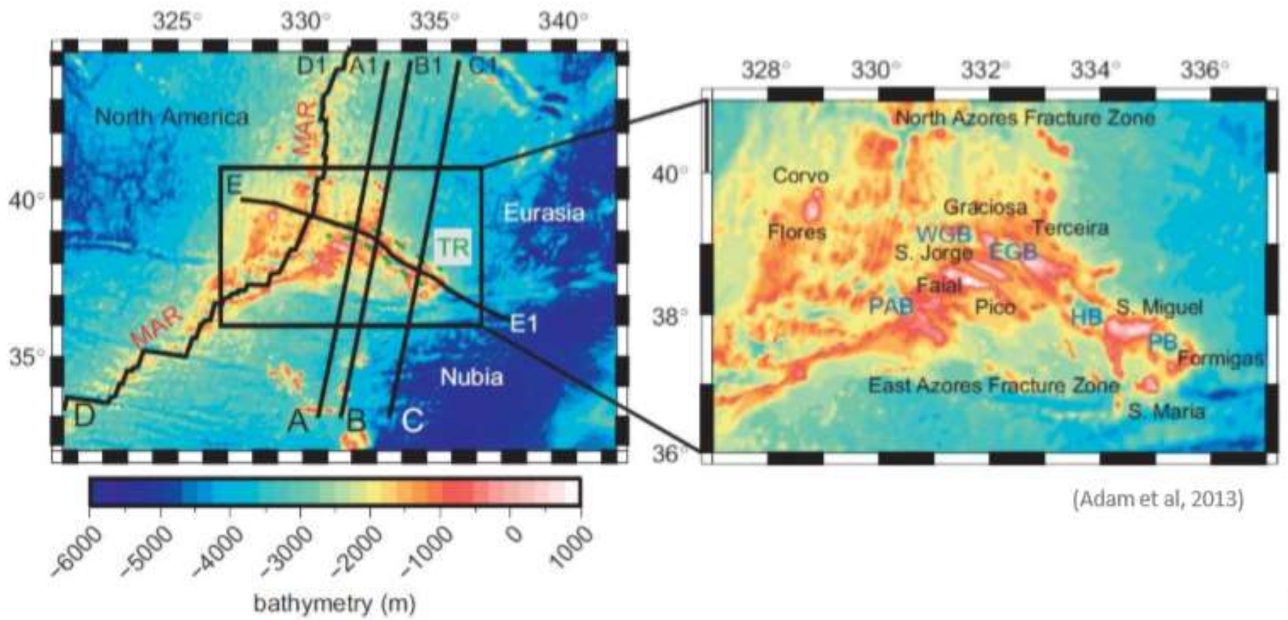
(Adam et al, 2013)

[.34.]

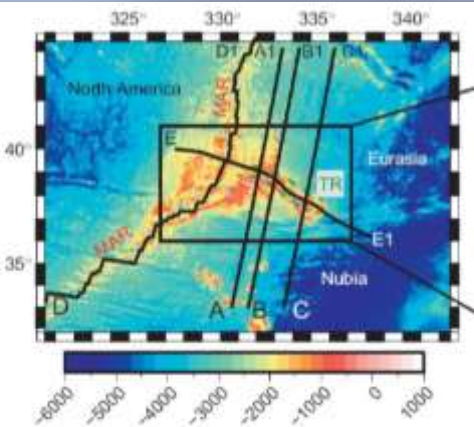
De Azoren

Looking inside the mantle

- The plume has been imaged by several tomography models.
- The characteristics of the plume vary according to different models concerning the wavelength and amplitude of the velocity anomalies, as well as the depth of the root.
- Is the 'Azores plume' a shallow feature of the upper mantle or does it extend to the whole mantle?
- We will first look into models from Adam et al (2013)
- See images for profile lines.



(Adam et al, 2013)



[.34.]

De Azoren

de the

Location of transections described on previous slide

The model points out two main low shallow (depth < 200km) velocity anomalies.

- One located under the islands Faial, Pico, S. Jorge, and Graciosa
- Other located under the area between the Terceira and S. Miguel islands

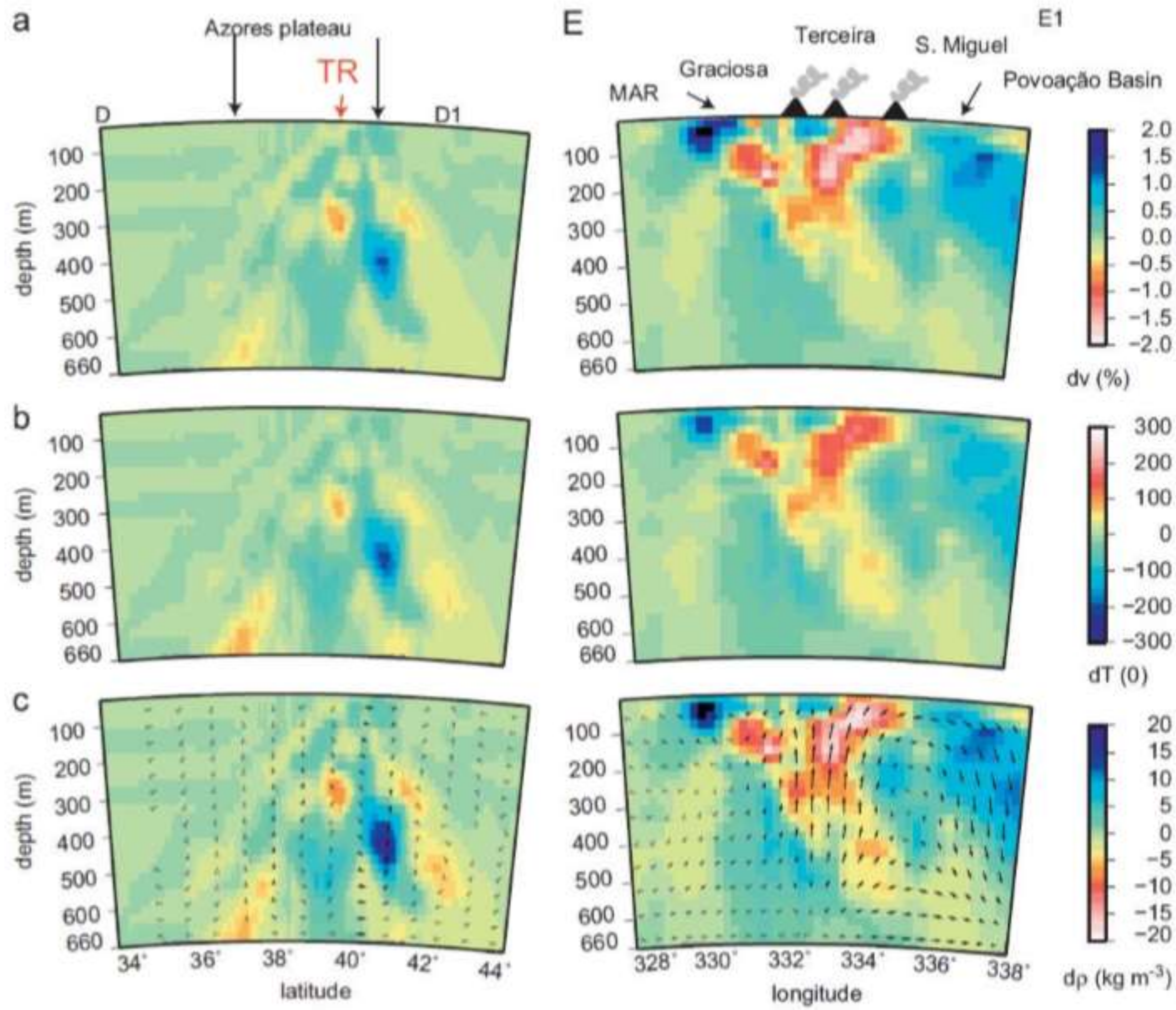


Fig. 2. Depth cross sections along the MAR (left panels) and the TR (right panels); (a) tomography model (Yang et al., 2006); (b) temperature anomalies deduced from the tomography model; (c) density anomalies deduced from the tomography model; the arrows represent the convection driven by these density anomalies.

(Adam et al, 2013)

De Azoren

Looking inside the mantle

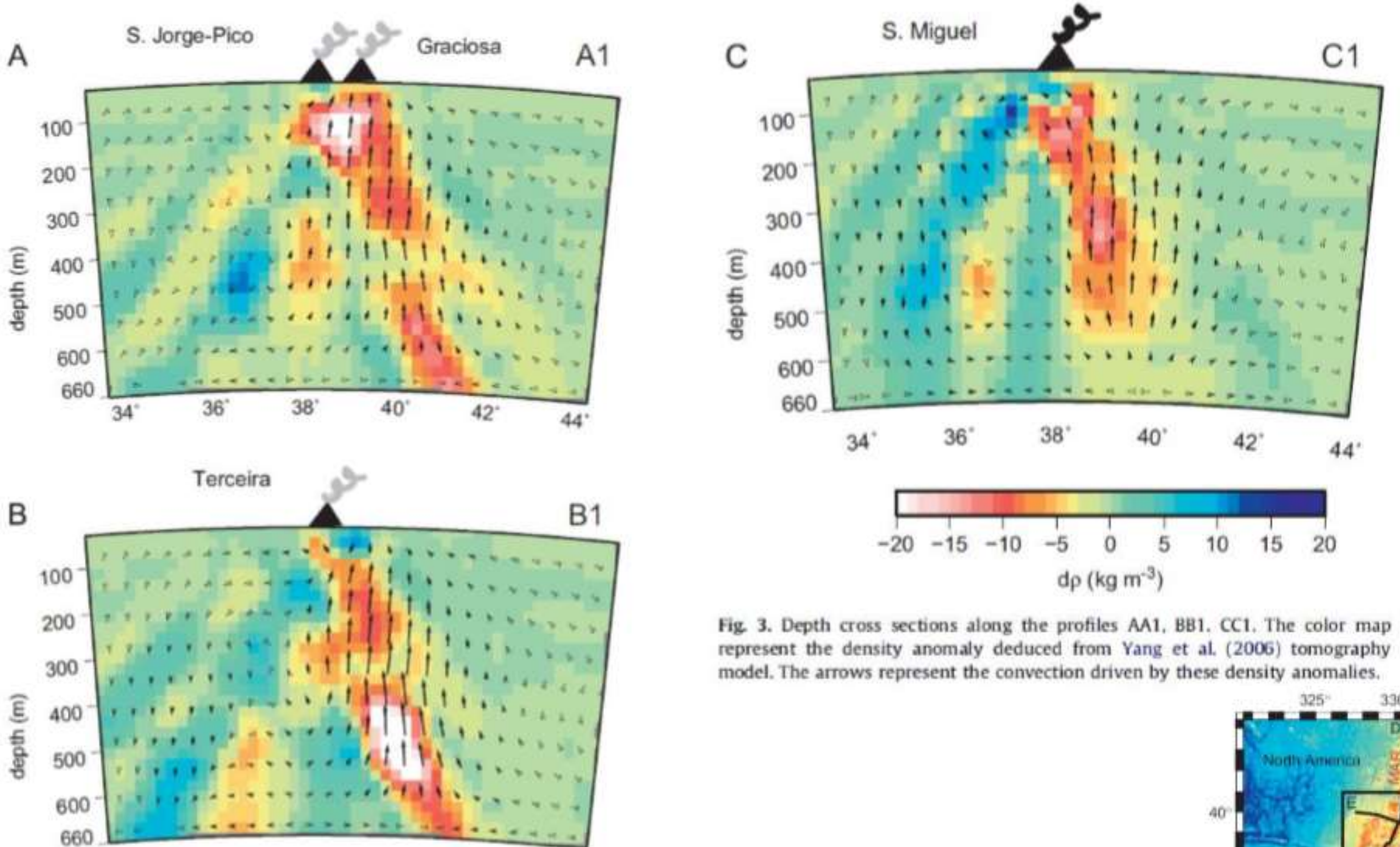
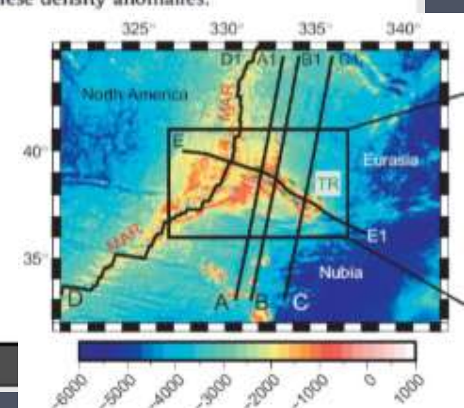


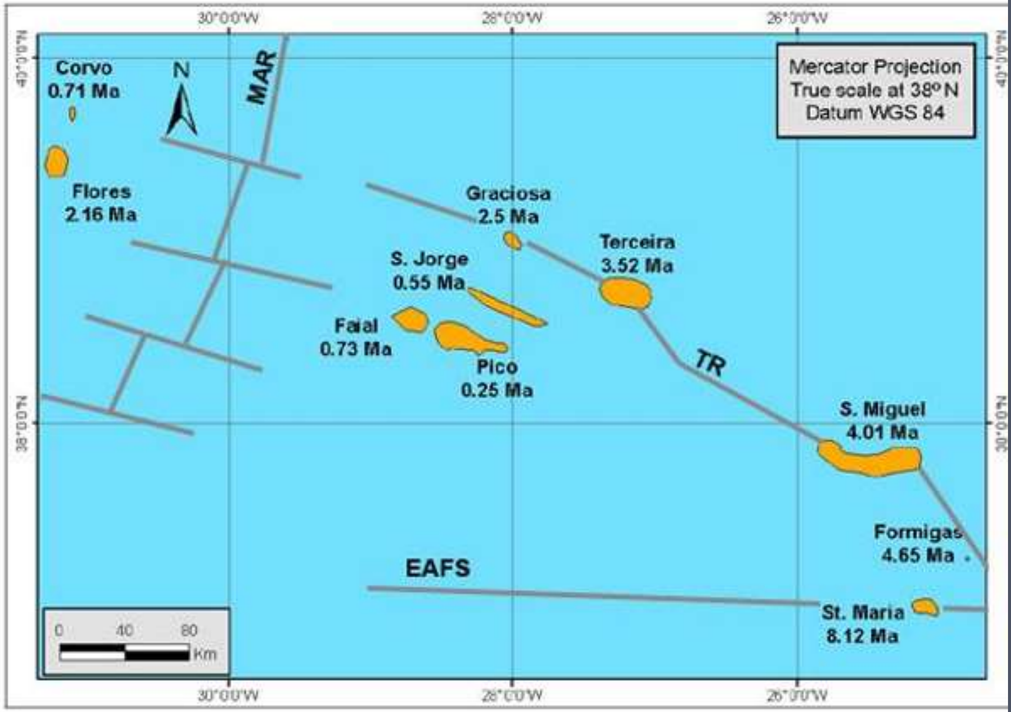
Fig. 3. Depth cross sections along the profiles AA1, BB1, CC1. The color map represent the density anomaly deduced from Yang et al. (2006) tomography model. The arrows represent the convection driven by these density anomalies.



[.34.]

Research on Helium isotopes in hydrothermal fluids of the Azores archipelago De Azoren

- Very wide range of the $^3He/^4He$ ratio
  - Lower-than-MORB values (5.23–6.07 Ra) on central Sao Miguel, (normalized to the air ratio, Ra)
  - MORB values on Faial (8.53 Ra) and Flores (8.04 Ra) – either side of MAR
  - Plume-type values on Graciosa (11.2 Ra) and Terceira (13.5 Ra), where free gases also display ten times higher-than-MORB $CO_2/^3He$ ratios (1.8–2.6×10^{10}).



- The simultaneity of both elevated $CO_2/^3He$ and $^3He/^4He$ ratios is best explained by a ^3He-rich contribution from the lower mantle diluted in a CO_2-rich feeding plume that contains a recycled altered oceanic plate component.

(Babtiste et al, 20

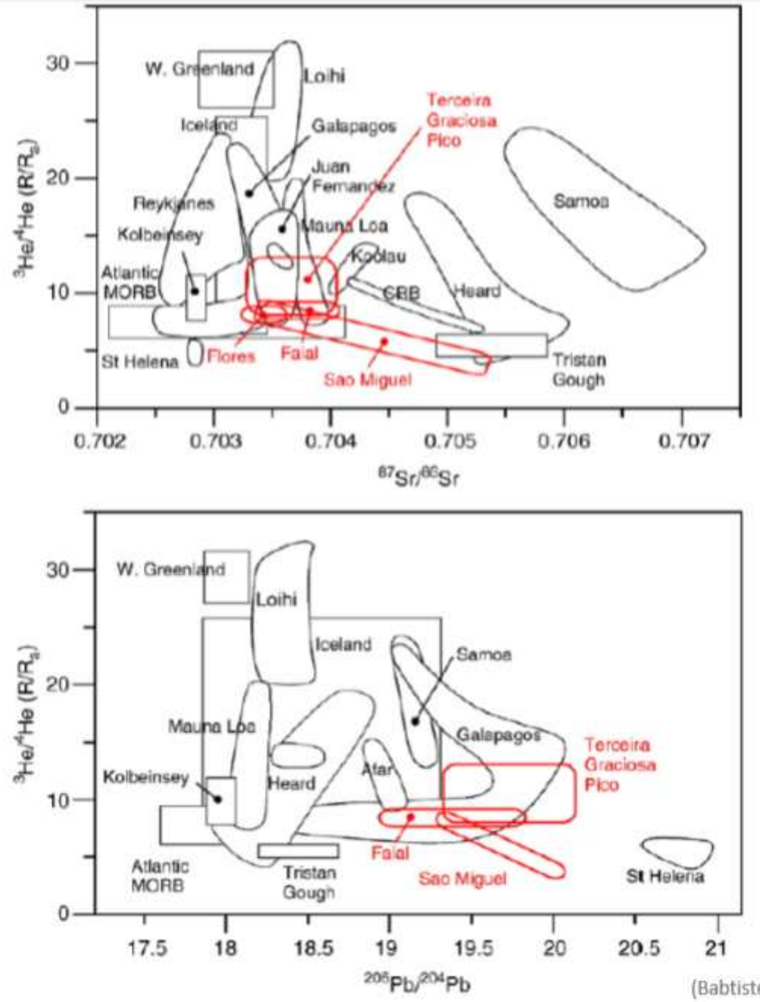
De Azoren

In relation to other areas

The observed isotopic variations require a mixing with at least two other mantle components:

(i) normal MORB mantle similar to that feeding the nearby Mid-Atlantic Ridge, and

(ii) a plumetype component with moderately high $^{3}He/^{4}He$ ratio and intermediate $^{87}Sr/^{86}Sr$ and $^{206}Pb/^{204}Pb$ values compared to themost 'primitive' endmember feeding Iceland or Loihi seamount in Hawaii



(Babtiste et al, 2009)

Fig. 4. He–Sr and He–Pb isotopic relations for Azores volcanic products (adapted from Graham et al., 1998). The helium isotope data set includes our present results for Azores fluids and those for volcanic rocks from Kurz (1991), Moreira et al. (1999), Madureira et al. (2005). Sr–Pb isotope data for Azores lavas are from White et al. (1976), Hawkesworth et al. (1979), Dupré et al. (1982), Davies et al. (1989), Widom et al. (1997), Turner et al. (1997), Moreira et al. (1999), França et al. (2006), and Beier et al. (2007).

De Azoren

Longitudinal distribution

The highest values (and plume-type) of $^3He/^4He$ ratios in fluids and rocks of the central volcanic islands demonstrates that the Azores plume component is concentrated under the central part of the archipelago.

However, the actual centre of the "high" $^3He/^4He$ plume might well be located beneath the island of Sao Jorge, just south of Terceira, where one rock sample with a ratio as high as 15.9 Ra has been reported.

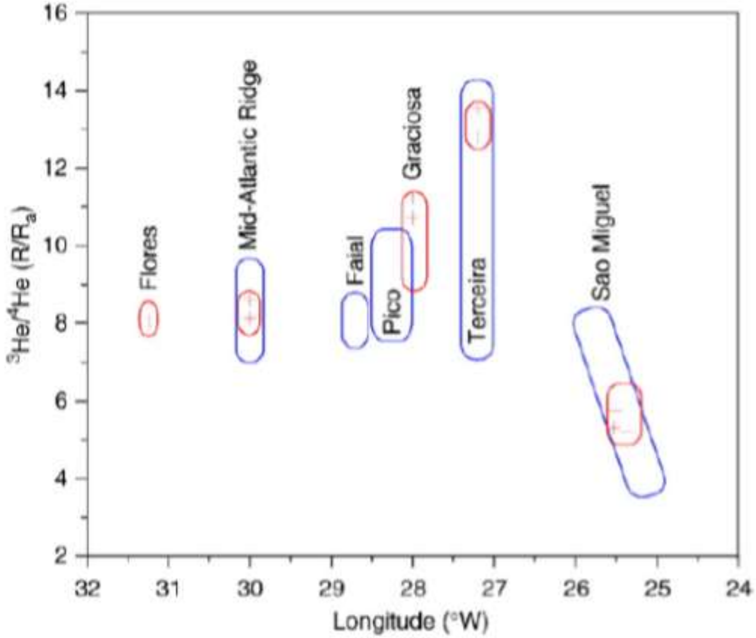


Fig. 5. Longitudinal distribution of $^3He/^4He$ ratios in Azores volcanic fluids and rocks. Rock data (in blue) are from Kurz (1991), Moreira et al. (1999) and Madureira et al. (2005). Our gas data are in red. Data for the Mid-Atlantic Ridge (37°N–40°N) rocks are from Moreira and Allègre (2002) and those for submarine hydrothermal fluid venting are from Jean-Baptiste et al. (1998) and Charlou et al. (2000).

(Babtiste et al, 2009)

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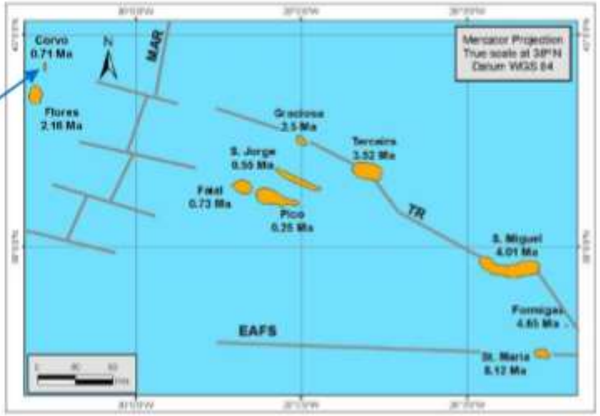
Geochemical composition: TAS Diagram

[.34.]



The data is for Corvo Island (the small island on the American plate).

According to Franca et al (2006) the geochemical composition for the Corvo island area nearly equivalent for other islands in the archipelago.

It seem to be above the Hawaiian line.

Described by the author as a material from a mantle plume with a significant HIMU (high time-integrated $^{238}U/^{204}Pb$ or high μ) contribution as the geodynamic scenario for the genesis of the magmas.

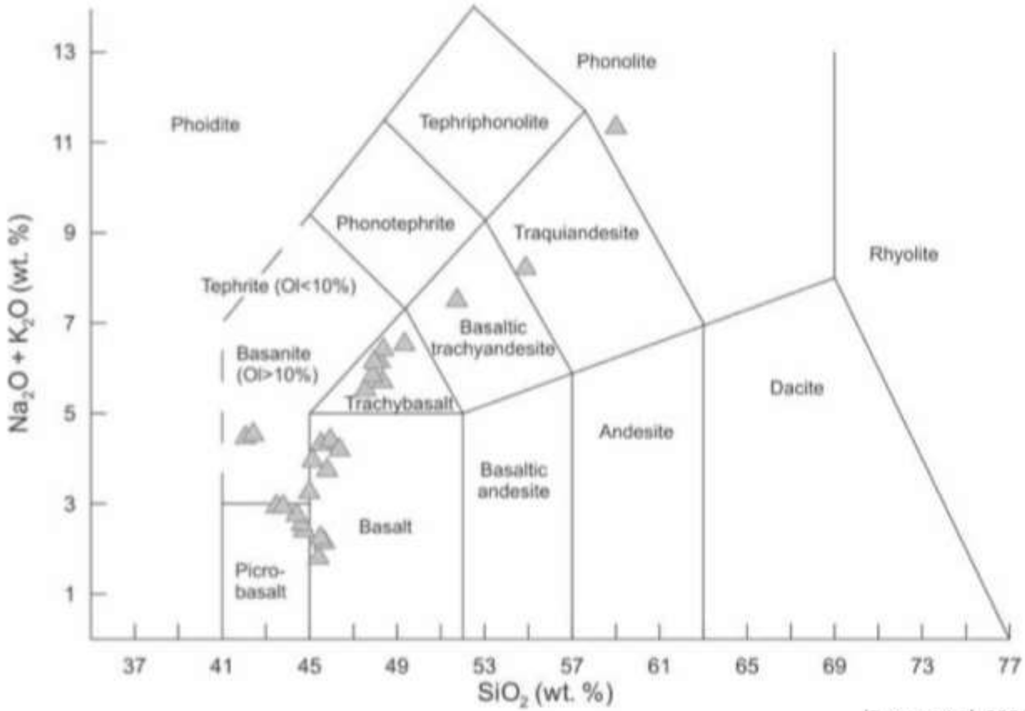


Fig. 2.- TAS diagram for 49 volcanic rocks of the Corvo island. (França et al, 2006)

The **gal** (symbol: Gal), sometimes called **galileo** after Galileo Galilei, is a unit of acceleration used extensively in the science of gravimetry.[2][3][4] The gal is defined as 1 centimeter per second squared (1 cm/s^2).

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Looking inside the mantle

Based on gravity study:

a) Bathymetry: Seefloor depth
b) Bouguer gravity anomaly
c) Residual
d) Relative crustal thickness, should be interpreted as upper bounds.

Seismic and gravity data suggest plateau crustal thicknesses of ~8 km or more

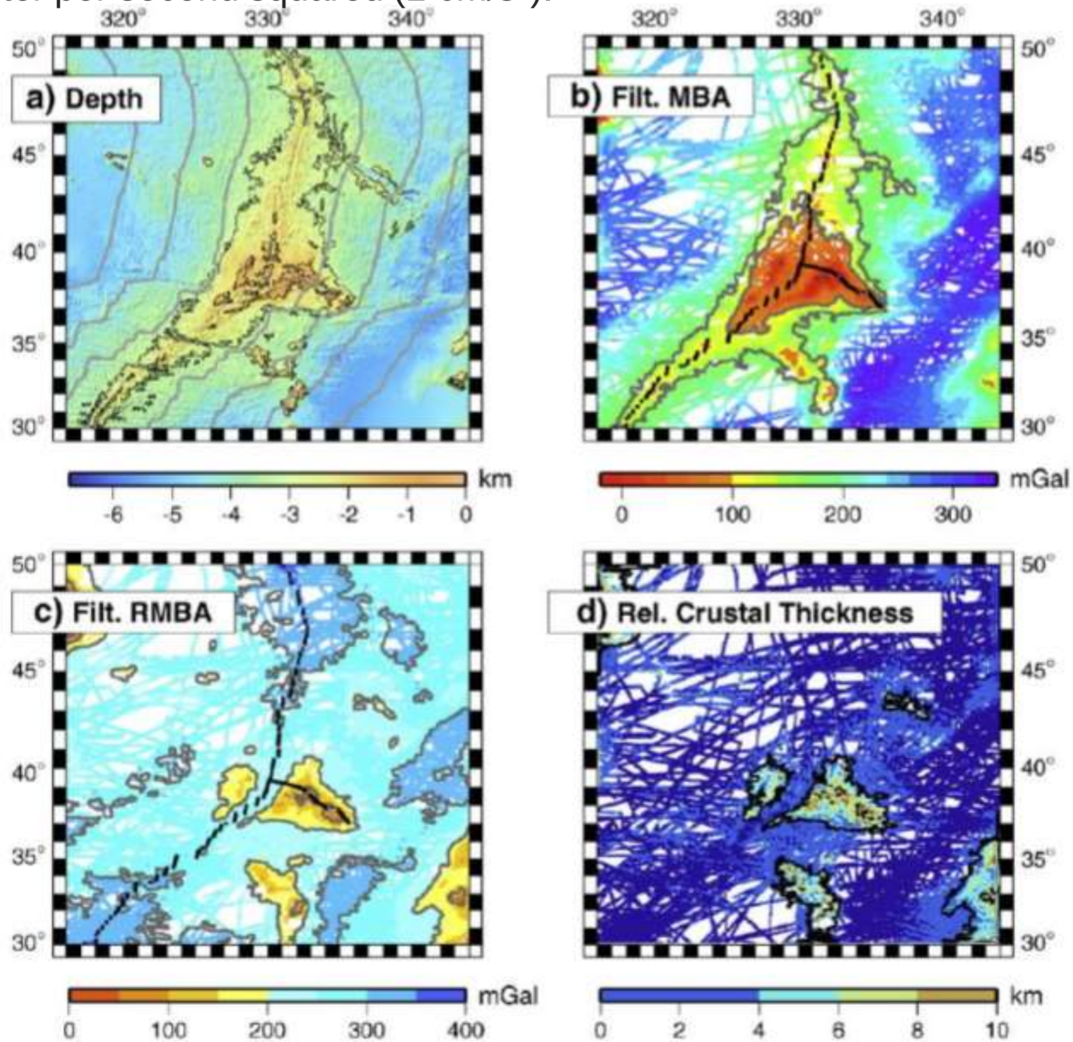

Fig. 3. (a) Seafloor depth, (b) mantle Bouguer anomaly, (c) residual mantle Bouguer anomaly, and (d) gravity-inferred relative crustal thickness variations for the Azores Triple Junction region. Data sources, data set resolution, and calculation methods are described in the text. Contours are plotted at (a) 1.5 km depth, (b) 100 and 160 mGal, (c) 100 mGal, and (d) 3 km. In (a), thick gray lines show 25 Myr isochrons (Müller et al., 2008). In (b), (c), and (d), regions farther than 10′ from a shiptrack are masked with white to visually deter interpretation of areas without data control. MBA and RMBA are filtered with a lowpass filter with cutoff wavelength of 40 km.

(Georgen & sankar, 2010)

[.34.]

[.34.]

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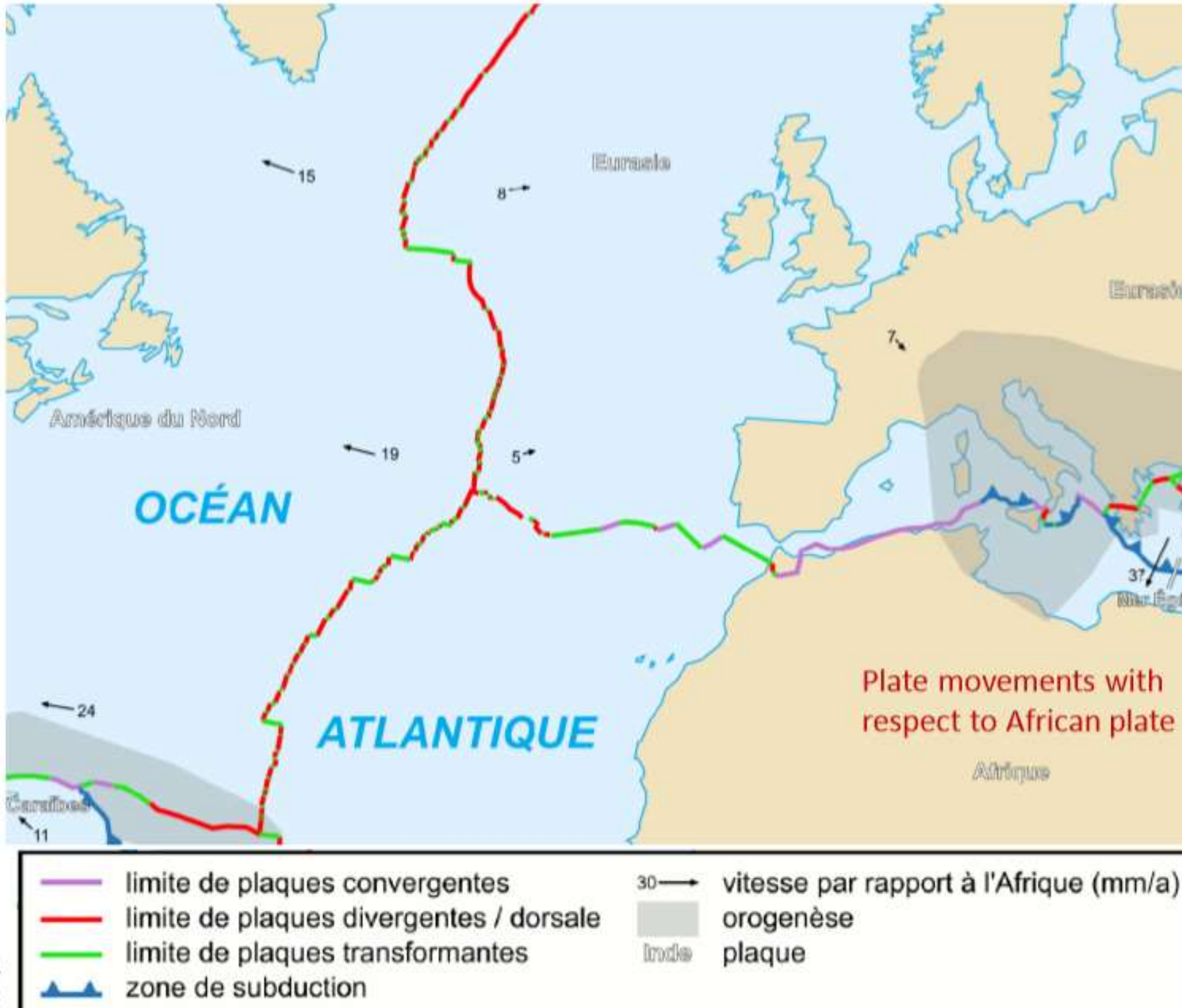
Plate tectonics

- The Azor Triple Junction: Ridge-Ridge-Ridge
- But: According to data from USGS used in Google klm file available on the internet it is Rige-Ridge-Transform triple junction



(Páll Einarsson, presentation 2012 in Current crustal)

[.34.]

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TER: Terceira Rift

- The precise nature of the TER has been debated
  - Some investigations describe the boundary as a zone of distributed deformation or as an extensional strike-slip fault [e.g., Luis et al., 1998].
  - Other [Vogt and Jung 2004] treats the TER as an ultra-slow diverging ridge with a half-rate of 0.4 cm/yr.

(Georgen, 2011)

- Slowest spreading rate on Earth?
  - The Gakkel Ridge in the Arctic area: 7-13mm/a
  - SW Indian Ridge: 15-16mm/a
  - Terceira Ridge: 4mm/a
- Topography of the ridge, Interpreted simply as volcanically ‘unfilled’ rift valley segments:
  - the interisland basins (e.g. the 3200 m deep Hirondelle Basin) are slightly wider (30-60 km), but not significantly deeper (1000-2200 m) than the Mid-Atlantic Ridge (MAR) median valley (20-28 mm/a)

(Vogt & jung, 2004)

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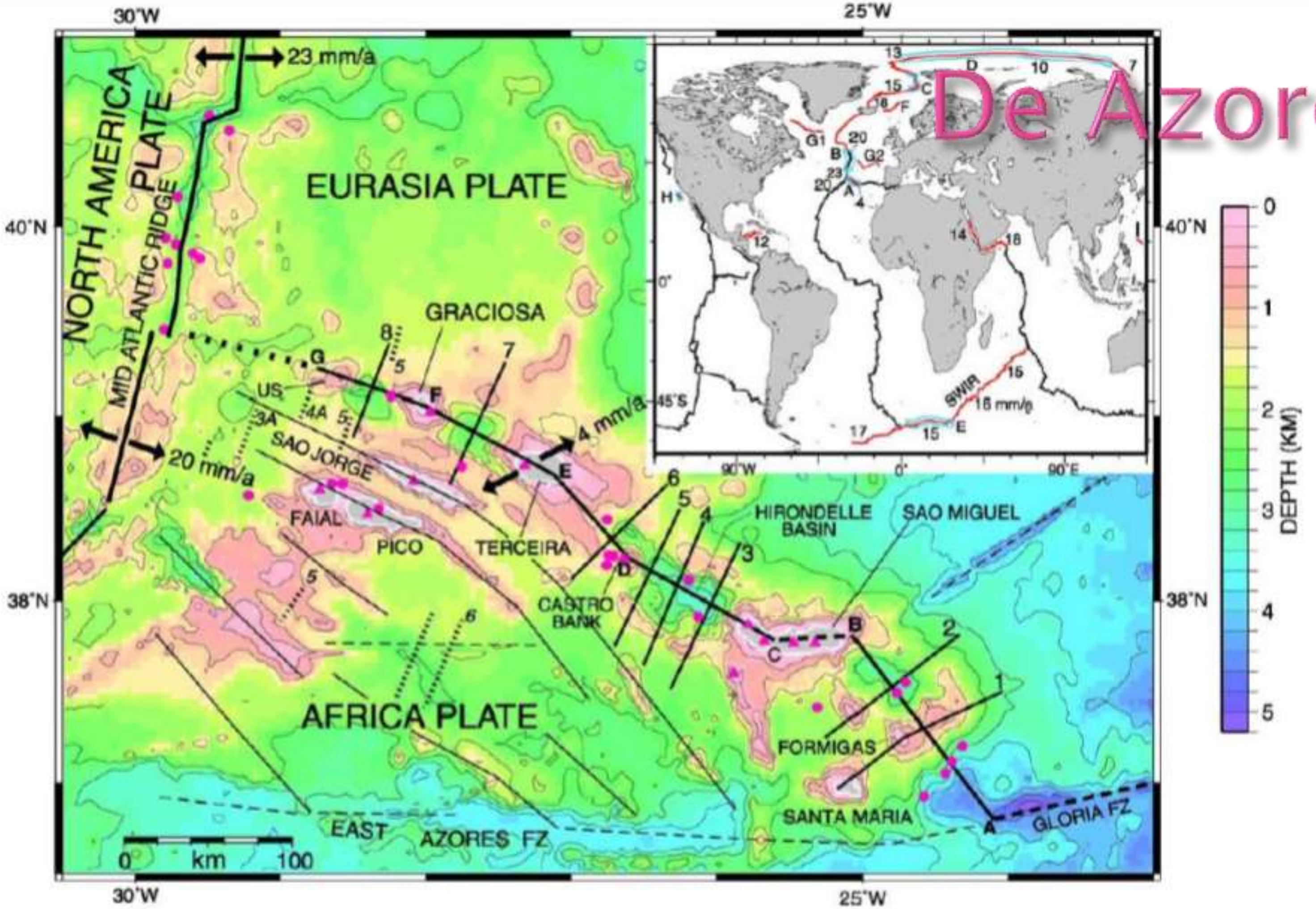


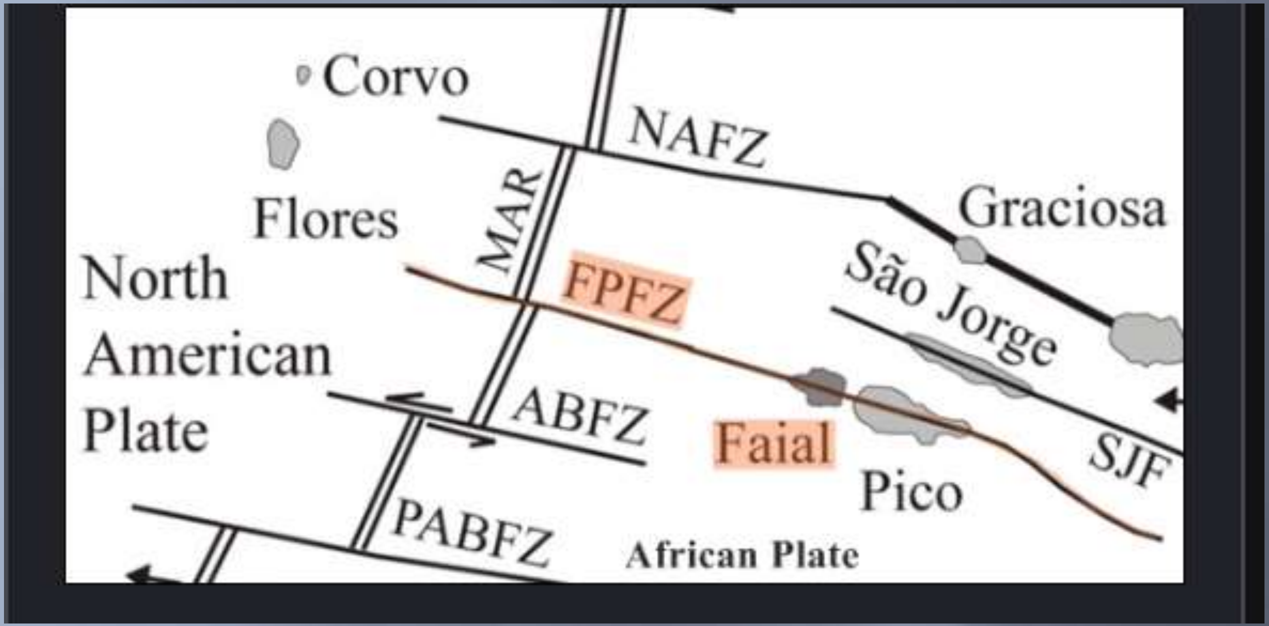
Fig. 1. Bathymetry of Azores Plateau area (from [32]), showing interpreted Terceira Rift and Mid-Atlantic Ridge plate boundaries (solid, spreading ridges; dashed, transform faults; dotted, uncertain boundary). Red dots are teleseisms (courtesy of National Geophysical Data Center) and triangles are active and dormant volcanoes. Thin solid and dashed lines show possible extinct, pre-TR plate boundaries. Dotted lines are sea-floor spreading type magnetic lineations (modified from [20]). Numbered lines show locations of bathymetric profiles, and letters denote points along longitudinal profile (Fig. 2). Inset map shows world's major spreading boundaries, with total opening rates (mm/a) for slow ridges. Lettered blue boxes outline locations of ridge segments reproduced in Fig. 4 and others discussed in text: A, Terceira Rift; B, Mid-Atlantic Ridge; C, Mohns-Knipovich Ridge; D, Gakkel (Nansen) Ridge; E, Southwest Indian Ridge; F, extinct Aegir Ridge; G1, extinct Mid-Labrador Sea Ridge; G2, King's Trough; H, Guadalupe Island and extinct axis; I, extinct West Philippine Sea axis.

[.34.]

(Vogt & jung, 2004)

For discussion

- Is the Terceira Rift the slowest rift on Earth?
- What will be the future of the Terceira Rift?
- Do we have a mantle plume at Azores – and even 2 of them?
- Why is much more volcanic material above sea level in Iceland than in the Azores?



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[.64.]

There are two main fault systems recognized in the Central Group. The dominant FPFZ, striking WNW-ESE, controls the general shape of the islands. The second, less obvious yet important fault system, is trending NNW-SSE. Volcanism is controlled by these tectonics: intersections of the two fault systems determine the location of polygenetic volcanoes, while monogenetic volcanoes lie mainly on WNW-ESE fault lines. One study from 2013 suggests that Faial, along with the nearby Pico Island, is a major locus of extension within the Azores, directly above the imaged hotspot.

De Azoren

[.37.] (2013)

In this study, we present and interpret GPS observations from sites in the Azores archipelago in the context of existing bathymetric/structural and seismic data to address three fundamental questions related to the Azores Triple Junction: (1) Is the Nubia–Eurasia plate boundary discrete or diffuse near the Azores Triple Junction and, by implication, is the triple junction discrete or diffuse? (2) Where is the present Nubia–Eurasia plate boundary in this region? (3) Is there an Azores microplate? Previous au-

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[.37.] (2013)

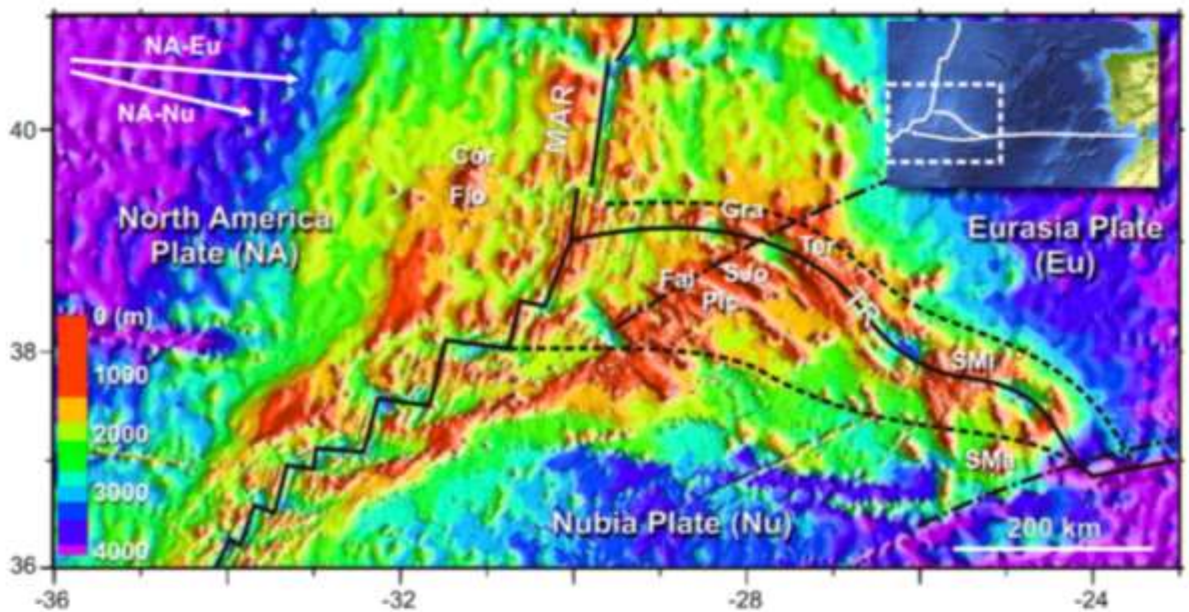


Fig. 1. Sketch illustrating the tectonic setting of the Azores Triple Junction. Inset on top right corner for location. Inset on top left corner for the kinematics of the Nubia and Eurasia lithospheric plates (DeMets et al., 2010). Dashed lines mark the boundaries of a hypothetical Azores microplate. Dash-dotted lines represent small circles around the MORVEL Nubia–Eurasia pole. The nine Azores islands are, from W to E, Corvo (Cor), Flores (Flo), Faial (Fai), Pico (Pic), S. Jorge (SJo), Graciosa (Gra), Terceira (Ter), S. Miguel (SMi), and Santa Maria (SMa).

De Azoren

[.37.] (2013)

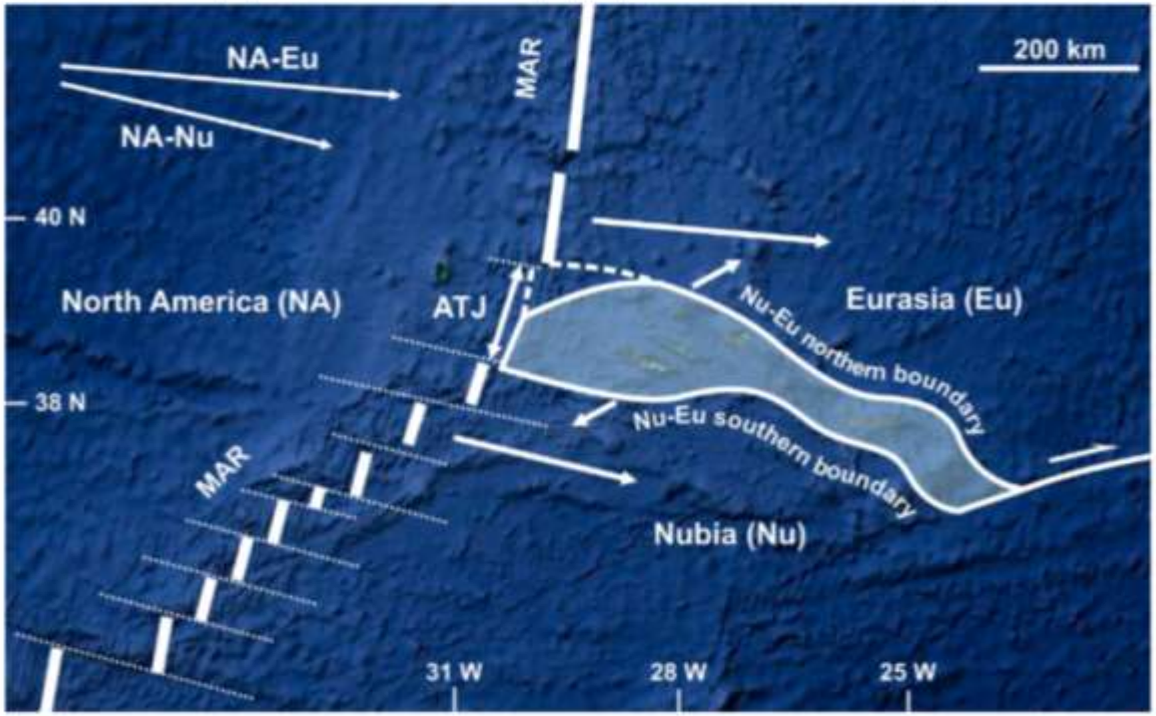
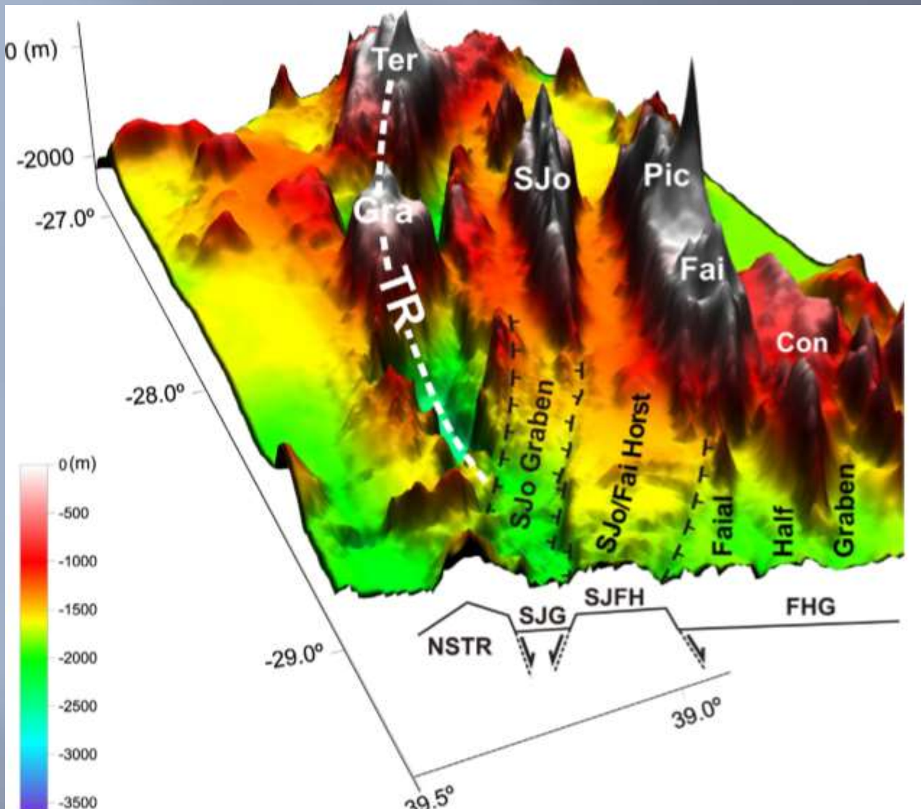


Fig. 8. Proposed Nu–Eu plate boundary in the Azores. Shadowed area is the diffuse plate boundary inferred from GPS, bathymetric, structural and seismic data. Inset on top left corner shows kinematics of the Nubia and Eurasia lithospheric plates (DeMets et al., 2010). Dotted lines represent transform faults. Background image is from Google.

De Azoren



[.37+38.] (2013)

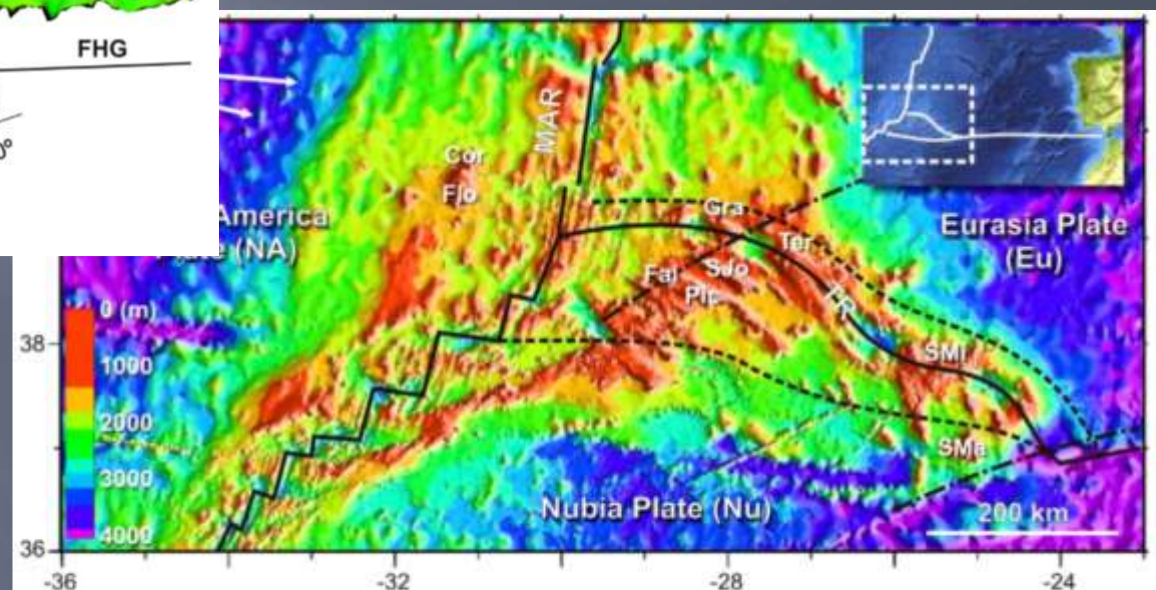


Fig. 1. Sketch illustrating the tectonic setting of the Azores Triple Junction. Inset on top right corner for location. Inset on top left corner for the kinematics of the Nubia and Eurasia lithospheric plates (DeMets et al., 2010). Dashed lines mark the boundaries of a hypothetical Azores microplate. Dash-dotted lines represent small circles around the MORVEL Nubia–Eurasia pole. The nine Azores islands are, from W to E, Corvo (Cor), Flores (Flo), Faial (Fai), Pico (Pic), S. Jorge (SJo), Graciosa (Gra), Terceira (Ter), S. Miguel (SMi), and Santa Maria (SMa).

Fig. 7. 3D surface built using available bathymetry data (http://w3.ualg.pt/~jluis/misc/ac_plateau1km.grd). Note the prominent graben-horst structure close to the junction between the TR and the MAR. The islands of Terceira (Ter), Graciosa (Gra), S. Jorge (SJo), Pico (Pic) and Faial (Fai) are shown. Con – Condor seamount. NSTR – northern shoulder of the Terceira Rift (TR). SJG – S. Jorge Graben. SJFH – S. Jorge/Faial Horst. FHG – Faial Half-graben. Vertical lighting.

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[.37.] (2013)

6. Conclusions

From newly determined GPS velocities from the Azores archipelago, and Eurasia and Nubia plates, we find that oblique WSW-ENE extension between the Nubia and Eurasia plates is accommodated across a series of horsts and grabens that include the Pico/Faial volcanic ridge, which moves mostly with Nubia, Terceira Island, which moves mostly with Eurasia, and S. Jorge Island, whose motion is intermediate between that of Nubia and Eurasia. From these observations and existing bathymetric and seismic data, we conclude the following:

1. The Nubia–Eurasia plate boundary at the longitude of the Azores is diffuse, comprising a ca. 140-km-wide zone of deformation shown in Fig. 8.
2. The opening rate in the Terceira Rift is much smaller than previously thought, because it does not take up the whole deformation imposed by the motions of Nubia and Eurasia.
3. The Azores Triple Junction is diffuse, stretching along the MAR axis between 38.3°N, 30.3°W and 39.4°N, 29.7°W, where spreading rates decrease gradually from ca. 22.5 mm/yr N of 40°N to 19.5 mm/yr S of 38°N.
4. The new data do not require the existence of an independent Azores microplate.

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J.M.M. Azevedo, M.R. Portugal Ferreira / Journal of Volcanology and Geothermal Research 156 (2006) 90–102 91

[~9 Ma ocean floor.]

[.39.]

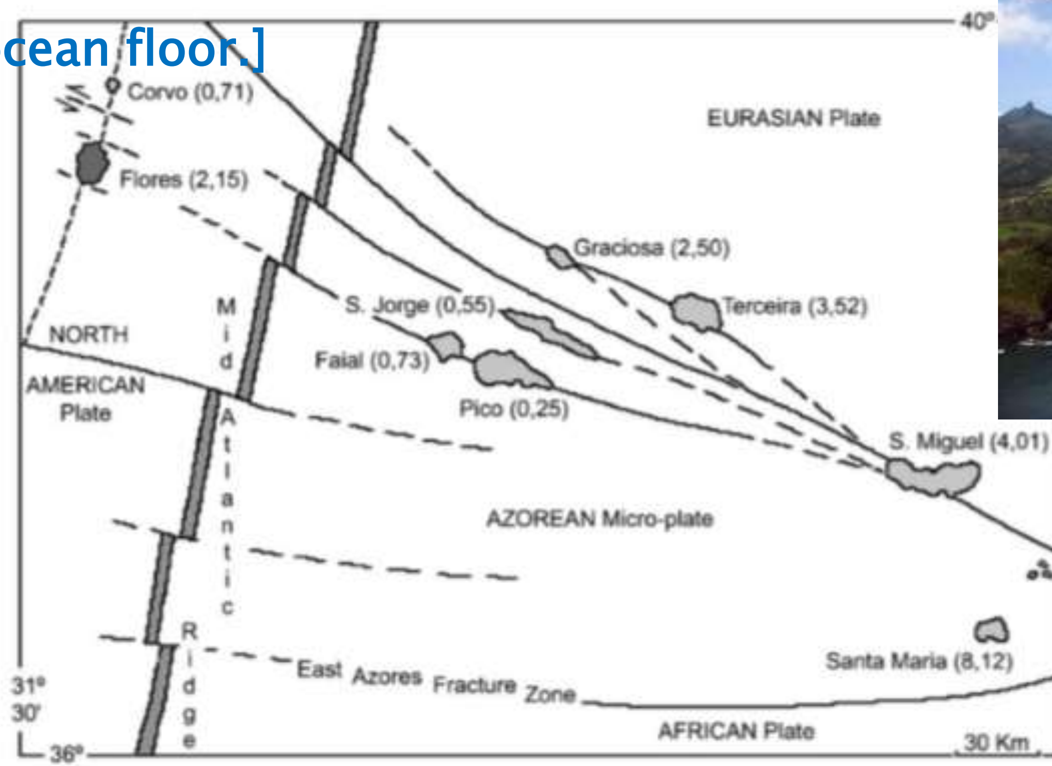

Fig. 1. Geographic and geotectonic setting of Azores Archipelago (adapted from Forjaz, 1988; Baptista et al., 1999) with the oldest radiometric ages (in parentheses; Ma) for each island (geochronological data from Abdel-Monem et al., 1968, 1975; White et al., 1976; Feraud et al., 1980; Ferreira and Martins, 1983; Feraud et al., 1984; Forjaz, 1988; Azevedo et al., 1991; Azevedo, 1999; Nunes, 1999; Azevedo et al., 2003).

Flores

From the study and interpretation of the volcanic products and structures of Flores Island, we infer that its volcanic history was dominated by two major periods: (1) proto-insular volcanism, which includes all the submarine and emergent activities; and (2) insular volcanism, consisting exclusively of subaerial eruptions. The first period includes two phases: (1) the oldest (2.2 to 1.5 Ma) of shallow submarine volcanism; (2) the youngest (1.0 to 0.75 Ma) includes emergent volcanism. Throughout the second period,

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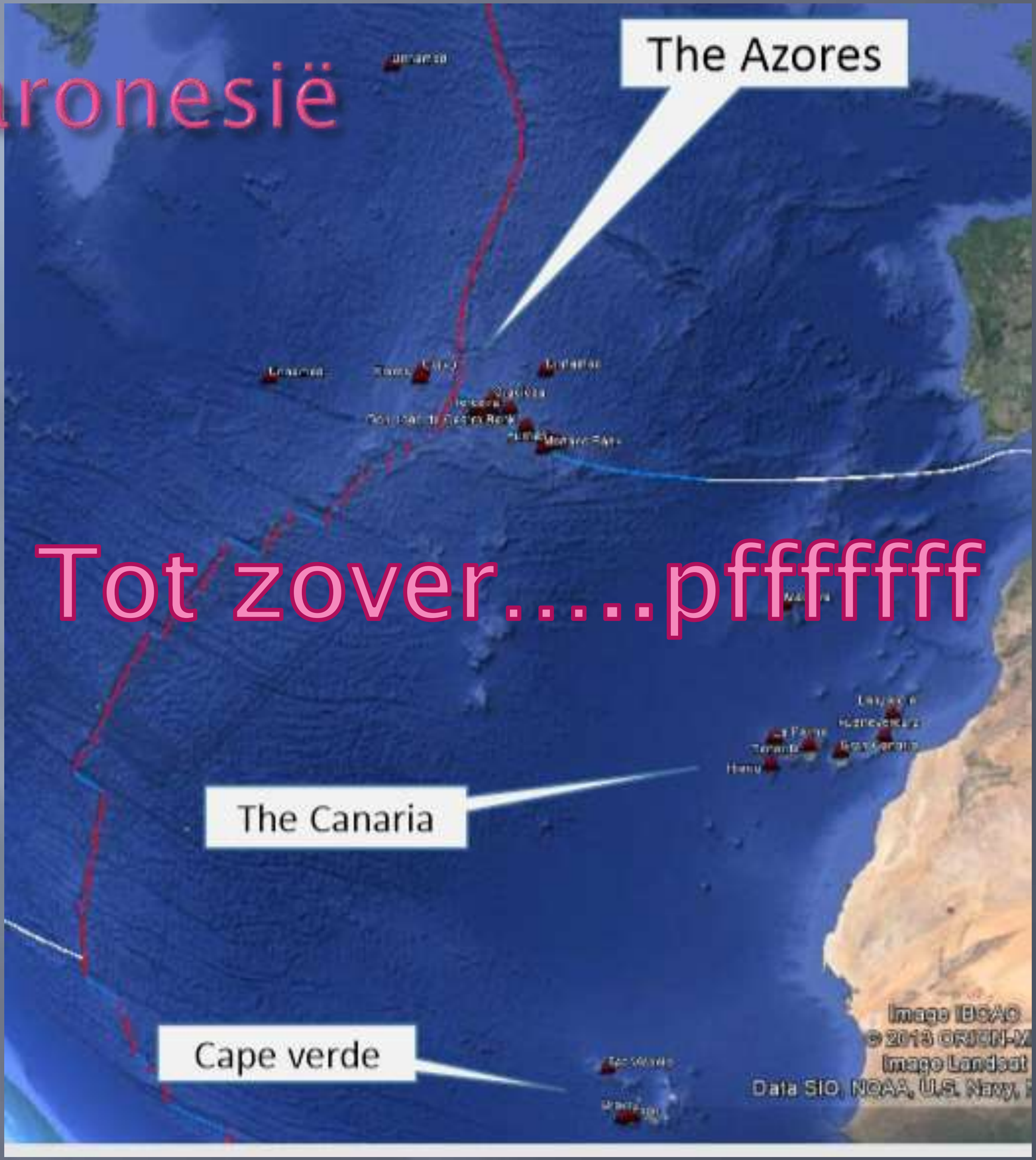
i) Sea floor stage. Volcanism to form the ocean floor started 10 Ma ago in the vicinity of the island that now corresponds to the seamount (BLAKELY 1974), and 9.0 Ma ago in the vicinity of Flores and Corvo (KRAUSE & WATKINS 1970).

ii) ii) Proto-island stage. This stage developed locally following formation of the volcanic ocean floor. The emergent volcanism of this phase lasted until 5.0 Ma ago at the site of the western bank and until 0.65 Ma ago in Flores.

iii) iii) Island stage. The basalts formed during this stage to form the western bank were formed 4.81 k 0.20 Ma ago. In Flores this stage started 0.65 Ma ago and continued until 0.2 Ma ago (MONSSEAU 1985). This subaerial volcanism was associated with uplift.

Inspite of a East-West trending fracture system on Flores, no such structure is known to occur between the two islands (Flores and Corvo) and the Mid-Atlantic Rift. It is, after all, a well known region for its seismic stability. However, it is possible that healed ancient fractures may exist. Such a structure is recognised in relation to the western branch of the EAFZ, between Santa Maria Island and the Middle Rift, and may have played an important role in the volcanism of that area.

Macaronesië



Tot zover.....pffffff

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